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Reducing pollution to levels not harming biodiversity and ecosystem functions: A perspective on the post-2020 Global Biodiversity Framework

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Abstract

Currently, there are more than 350,000 chemicals in use, while their ecological effects are not fully understood. In this review, we focus on pesticides, pharmaceuticals, and personal care products and discuss their potential impact on aquatic biodiversity and ecosystem functions. We critically reflect on strategies to reduce their environmental release and mitigate potential effects. Various mitigation strategies are available to reduce contaminant concentrations in surface waters, but their efficiency varies under the current procedures. Intervening at the start of chemicals' life cycles or reducing their diversity and production amounts holds promise for reducing surface water exposure. This approach could facilitate appropriate environmental risk assessments for each authorized chemical.

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Introduction

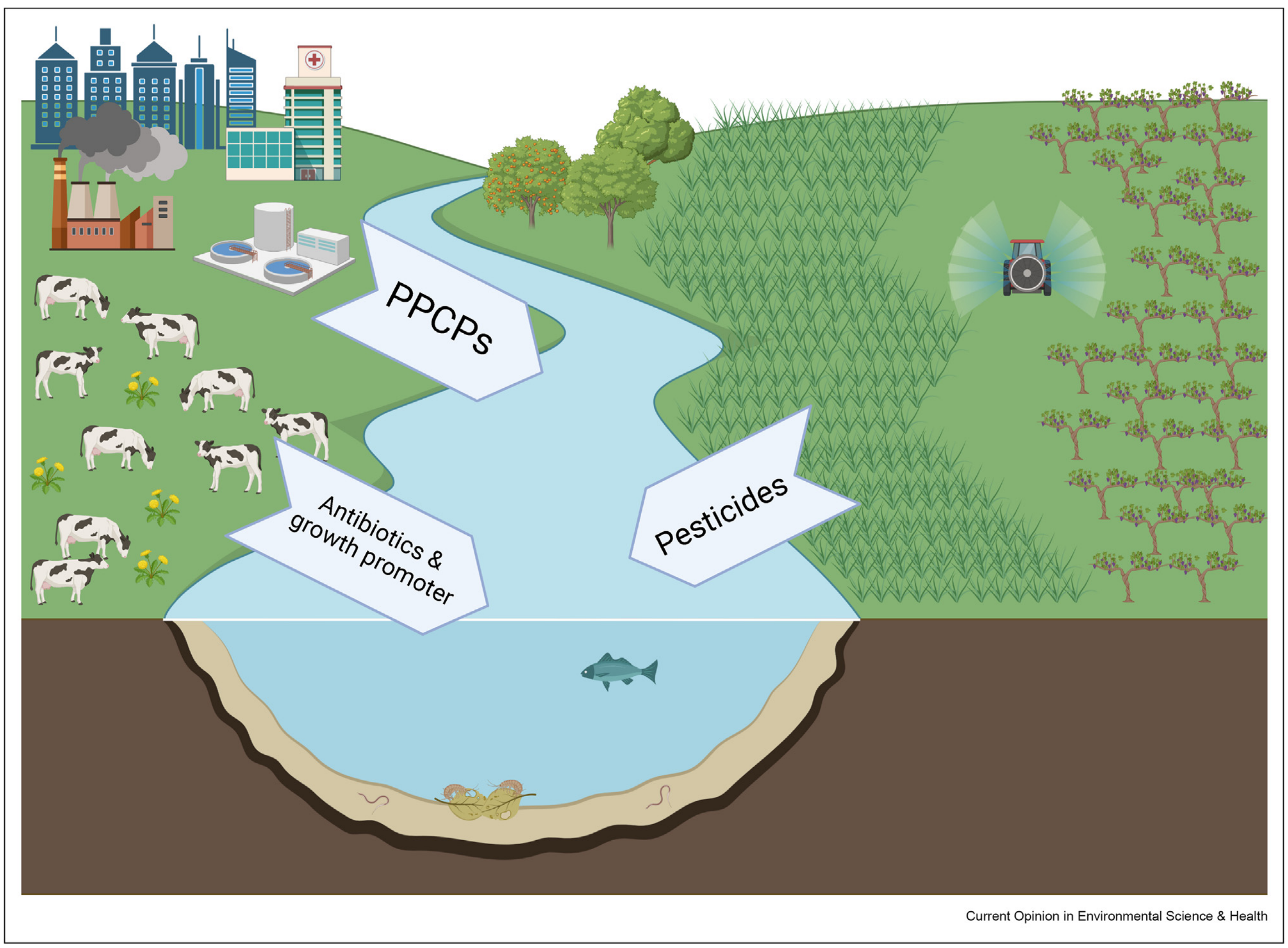
Chemicals, the term is here interpreted in its widest sense, are central to most if not all human activities on our planet to increase the efficiency in businesses, support human and animal health, and enhance the overall experience during spare time activities [sensu 1]. This wide use of chemicals is reflected by an estimated 100,000 chemicals being in commerce in the European Union (EU) [2], of which, according to the European Chemical Agency (ECHA), more than 25,000 chemicals are currently registered under the REACH framework (produced or imported equal to or above 1 ton per year) [3]. Roughly 240 and 80 million tons out of a total production volume of 300 million tons are considered as hazardous to human health and the environment, respectively [4]. Globally, over 350,000 chemicals have been registered for production and use [1], while for the majority of these chemicals and their transformation products, information of their ecotoxicological potential is lacking or incomplete [2]. The number of chemicals in combination with their production volume, of which approximately 25% are known to be hazardous to the environment, and the massive lack of information regarding their potential environmental impact illustrate the field of tension in which the current way of life contrasts a sustainable use of natural resources with consequences for biodiversity and ecosystem functions [5]. Ultimately, our current life or economic activity has initiated and accelerated the "chemization" of natural environments [5−7] and by doing so also threatened biodiversity and its associated functions through pollution [8−10].

With the aim to "reduce pollution from all sources to levels that are not harmful to biodiversity and ecosystem functions," the post-2020 Global Biodiversity Framework addresses exactly this challenge with special attention to nutrients, pesticides, and plastic waste [11]. Being an ambitious goal, it is also holistic in nature. In the present contribution, however, we focus on aquatic ecosystems motivated by their concave location in the landscape collecting chemicals used in their catchments [12]. Moreover, we address a subset of chemicals some of which are also specifically addressed by this target (that is agrochemicals represented by pesticides) as well as pharmaceuticals — both of which have intended biological effects. This focus is further motivated by the fact that more than 400 agrochemicals (e.g., pesticides) are approved for use in the EU [13], and more than 3000 active pharmaceutical ingredients are currently regulated in the EU [14]. This selection of chemicals additionally allows us to address point and diffuse (nonpoint) sources of pollution, which are discussed against the current state of knowledge regarding their effects. We also highlight some measures proposed in the literature to mitigate their impacts.

Pesticides in the aquatic environment — framing the problem

Pesticides are applied to agricultural fields to protect crops from pests such as insects, fungi, and weeds (Figure 1). As an early example, dichlorodiphenyltrichloroethane, also known under the abbreviation DDT, is an organochlorine insecticide that was first used to control vector-borne diseases in the second half of World War II and was later used in agriculture, with a substantial historical footprint: DDT attracted attention in the 1960s as its agricultural use was correlated to environmental impacts exemplified by eggshell thinning and ultimately declines in bird populations [15]. This organochlorine insecticide was subsequently banned in 1972 for agricultural use in the USA and in the 2000s worldwide, due to its high persistence, bioaccumulative properties, and endocrine activity [16]. Obviously, this is an example of just one pesticide, while several hundred pesticides are applied today with high total application amounts reaching or partly exceeding 60 kg ha^{-1} a year [17]. However, today's pesticide problems may no longer be as graspable as they were for DDT [18], which was traceable through the food chain, persistent in nature, and thus analytically quantifiable over long time periods in various environmental compartments (e.g.,

Figure 1



Schematic overview showing potential entry paths of chemicals into surface water bodies, where they pose risks for biodiversity and ecosystem functions. The scheme depicts the worst-case situation without management applications, which could reduce the influx of chemicals into surface water bodies. The delineated chemicals include pesticides (fungicides, herbicides, and insecticides) originating from agricultural fields (right side), pharmaceuticals and personal care products (PPCPs) from domestic households, hospitals, pharmaceutical formulation facilities, as well as wastewater treatment plants, and antibiotics and growth promoters from livestock production (left side). The breadth of the arrows indicates the amount of chemicals that enter surface waters. Created with BioRender.com.

biota or sediments). Today's pesticide problems could rather be characterized as more complex, intertwined, ephemeral but still spatially expansive.

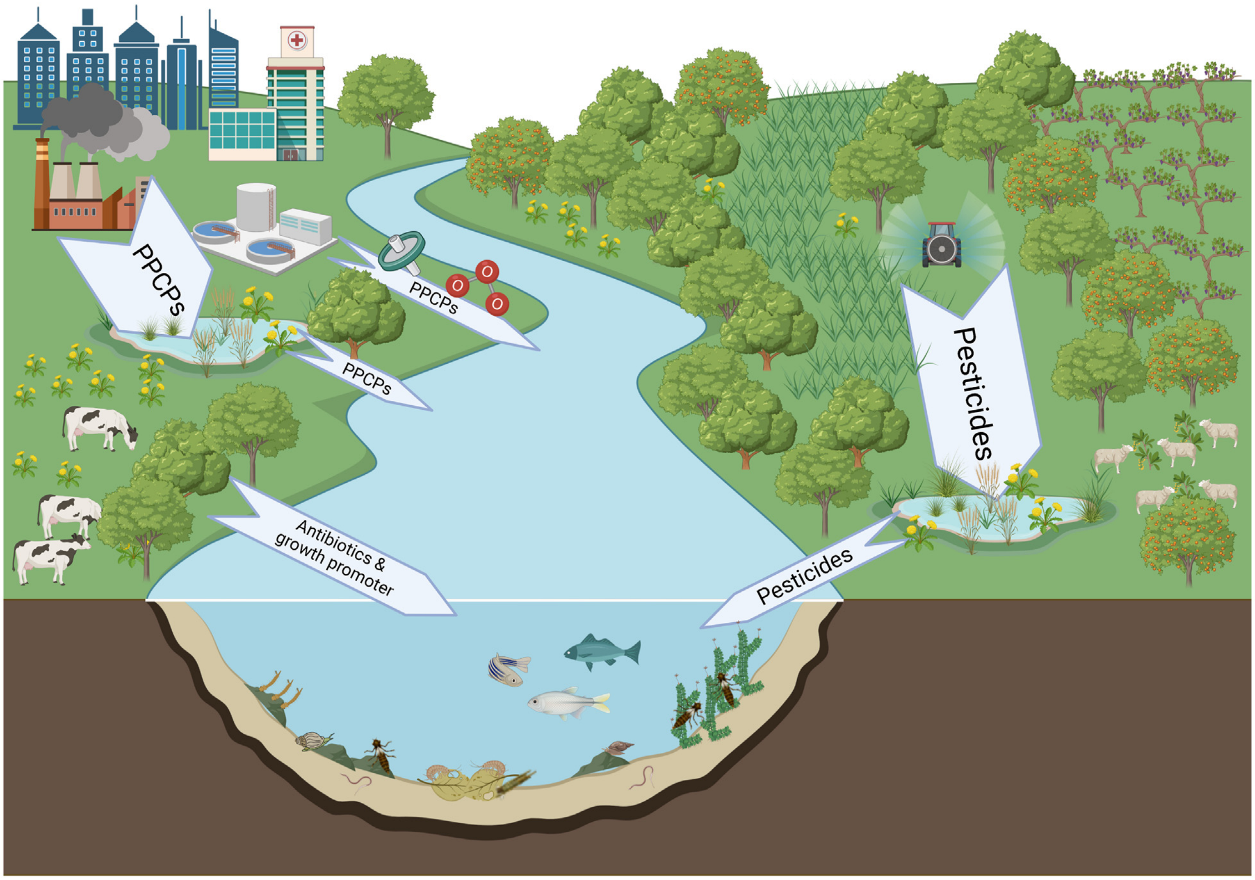
A meta-analysis from 2013 covering regions in Germany, France, and Australia pointed to negative impacts of pesticides on aquatic invertebrate biodiversity in agricultural streams (Figure 1) [19]. The authors also documented that the effect size, or the magnitude of change in biodiversity, is positively correlated with the toxic units of pesticides measured during the study duration at the sampling sites. Toxic units refer to measured pesticide concentrations being normalized by their ecotoxicological potential taking advantage of median effect concentrations determined during (non) standardized laboratory-based dose−response assays [20]. In other words, the impact on biodiversity increased with increased pesticide concentration, more specifically with the ecotoxicological potential of the locally measured pesticide mixture. Losses in macroinvertebrate species being considered sensitive to pesticide contamination have also yielded a positive correlation with the ecosystem function organic matter decomposition in streams, suggesting an indirect link between loss in macroinvertebrate biodiversity and ecosystem-level function that may propagate along the food web [10]. These effects were partly recorded at pesticide concentrations being considered as environmentally protective (e.g., below regulatory threshold levels [RTLs]) calling for further attention. This call is further substantiated by a global meta-analysis of approximately 11,000 measured insecticide concentrations in surface waters and sediments: Stehle and Schulz [9] report that in more than 50% of the cases, the RTL is exceeded. Similarly, comprehensive evaluations highlighted that surface waters throughout Europe ($n > 8000$) are to an even increasing extent exposed to pesticides at concentrations potentially affecting important species groups (e.g., invertebrates and plants) [21,22]. In the light of reported effects on biodiversity and ecosystem functions at concentrations below the RTL, these studies jointly point toward the significance of pesticides for the disruption of ecosystem integrity of agricultural streams.

Pesticides in the aquatic environment — potential solutions

Reducing pesticide application might be viewed — also according to the post-2020 Global Biodiversity Framework — as a significant measure to limit effects on regional biodiversity and ecosystem functions. However, a recent study by Schulz et al. [18] suggests that a reduction in the applied amount of pesticides does not necessarily result in a lower ecotoxicological potential of the total pesticide cocktail being applied to agricultural fields. Reducing the application of one group of insecticides usually leads to a replacement by another group of insecticides ensuring plant protection. This procedure may shift risks from one taxon to another taxon. In their publication, Schulz et al. [18] highlight that a reduction in organophosphate and carbamate applications reduced the total applied toxicity for fish, mammals, and birds. At the same time, these classes of insecticides have been replaced mainly by pyrethroids and neonicotinoids, resulting in a substantial increase in the total applied toxicity for aquatic invertebrates as well as pollinators, though lower pesticide amounts are applied. Similarly, in Europe, the recent ban of most neonicotinoids has or will shift agricultural producers toward other pesticides, most of which will be pyrethroids [23]. This strategy may, as shown in France, shift the ecotoxicological burden from pollinators to aquatic invertebrates and fish [23]. These insights challenge the belief that a reduction in the amounts of pesticide application will indeed lead to a reduction in their effects in the environment as the protection of crops still needs to be achieved with the use of more efficient pesticides. While such a strategy might reduce the potential risk for some taxa, this is to the expense of others, calling for a holistic framework.

During and following pesticide application, spray drift and surface runoff are processes carrying pesticides from agricultural fields into adjacent water bodies. Spray drift is, among others, a function of wind speed carrying pesticides during spraying in the direction of the stream [24], which is partly mitigated by regulations prohibiting spraying when a certain wind speed is exceeded as well as the use of proper spraying equipment [25]. Moreover, shrubs and trees in the riparian vegetation can buffer the entry of pesticides through spray drift functioning as a barrier [26]. Similarly, riparian vegetation could retain runoff, and thus, the pesticides get carried with the runoff into the local stream (Figure 2) [27,28]. However, the effectiveness of such measures is significantly reduced by erosion rills functioning as preferential flow pathways directly guiding runoff into surface water bodies [29−31]. Consequently, the release of pesticides from agricultural fields to adjacent water bodies through spray drift and runoff may be mitigated only to a certain extent, which greatly depends on a proper landscape management (drainage might reduce mitigation measures [32,33]) including the optimization of the riparian vegetation to retain pesticides during spraying and runoff events (Figure 2) [34]. Furthermore, fieldwork with heavy machinery, such as tractors or harvesters, should only be carried out perpendicular to the slope of the field to create track groves that intercept runoff water and prevent it from flowing over the edge of the field. However, the uncertainty regarding the short- and long-term efficiency of these measures calls for a significant reduction of pesticide application (both in amounts and toxicity equivalents) as also suggested by the European Green Deal [35]. Although these nonpoint sources of pollution remain a widespread contaminant pathway, the influence of point sources of

Figure 2



Schematic overview of potential management applications to reduce the influx of chemicals into surface water bodies. These management applications include vegetated buffer strips, shrubs, and trees in the riparian vegetation that act as spray drift barriers and buffer the entry of pesticides; vegetated systems like natural or constructed wetlands that function as retention basins for pesticides, pharmaceuticals, and personal care products (PPCPs), due to a directed influx of chemicals into vegetated systems via drainage ditches (agriculture) or sewage channels (wastewater treatment plants); reducing the demand for animal protein, depicted as smaller livestock production, to minimize the amount of applied antibiotics and growth promoters that are ultimately transported into surface waters via animals' excretions; advanced treatment techniques applied during wastewater treatment, such as ozone oxidation (depicted as ozone molecule) and the use of granular activated carbon filters, to reduce the loads of PPCPs. The width of the arrows indicates the amount of chemicals that enter surface waters. Ultimately, these management applications should contribute to safeguarding aquatic biodiversity and ecosystem functioning. Created with BioRender.com.

pesticides also requires attention. For instance, confined animal feeding operations, stormwater runoff, and wastewater treatment effluents are known point sources substantially contributing to the transfer of pesticides into aquatic systems, particularly in urbanized areas [36].

Once pesticides have entered the surface water body, vegetated systems such as natural or constructed wetlands could further mitigate potential negative impacts (Figure 2). Indeed, the suitability of these systems to reduce the concentration of hydrophobic insecticides was demonstrated with removal efficiencies partly above 90% [reviewed in 37]. The reduction is driven by adsorption to sediments and macrophytes [38] or the trapping of the suspended particles carrying the insecticides [39]. In addition to these processes, photolysis, hydrolysis, and microbial degradation were suggested as main drivers for the reduction of pesticide concentrations in vegetated systems [40]. Also, for less hydrophilic pesticides, such as fungicides, vegetated systems lead to partly high retention (up to 100%) depending on physicochemical properties of the pesticide and system inherent characteristics [41]. In a case study within a vine-growing area in Germany, for example, vegetated treatment systems reduced the peak concentration of fungicides reflected by a lower ecotoxicological potential for fish, invertebrates, and algae. The efficiency to reduce this ecotoxicological potential is mainly explained by plant density and size-related properties of the systems [42]. Hence, these vegetated treatment systems can indeed play a significant role in the mitigation of pesticide effects within agricultural streams if relevant factors are considered. Using natural vegetation cover and its retention potential advantageously, this strategy will require reassessing some currently applied management strategies such as regular dredging or scraping of surface ditches, which may severely reduce aforementioned benefits for containment degradation [43]. However, aquatic plants in vegetated treatment systems may only initially act as a sink for contaminants becoming a source once stable compounds desorb [44] or, when taken up into the plant, being consumed by detritivores [45].

Pharmaceuticals and personal care products in the aquatic environment — is there a risk?

The attention toward pharmaceuticals and personal care products (PPCPs) as aquatic contaminants of emerging concern has been growing over the last 20 plus years due to their extensive application for human and veterinary disease prophylaxis and treatment [6,46,47], growth promotion [48], and the prevention of bacteria-induced crop damage [49]. PPCPs cover a wide range of chemical classes including pharmaceuticals, such as antibiotics, anti-inflammatory drugs, painkillers, β-blockers, anti-epileptics, as well as personal care product ingredients, such as antimicrobials, synthetic musks, insect repellents, and sunscreen UV filters (as reviewed in Ref. [50]). In the last years, two main reasons caused the observed increase of PPCPs' global use and consumption: on the one hand, the worldwide increase in PPCP use by humans. In addition, the amplified level of prosperity coupled with easy-to-access medicines contributed to an increased use of PPCPs. On the other hand, the raising demand for animal proteins intensifies livestock and crop production that requires a significantly higher use of growth promoters and antibiotics [51,52]. Despite their widespread global use, PPCPs were largely underrepresented in large-scale monitoring programs until the 2010s. Until then, only usual suspects such as diclofenac and carbamazepine were monitored. This is reflected in a meta-analysis by Wolfram et al. [22] on the occurrence of organic chemicals in surface waters throughout Europe, where only ~0.5% of measurements (35,000 out of 8.3 mil) were related to PPCPs indicating a blind spot in our understanding of surface water contamination.

Because of their incomplete metabolization and degradation, substantial amounts of many PPCPs used by humans and for livestock are frequently detected in effluents of wastewater treatment plants, livestock production facilities, and hospitals (Figure 1) [53,54] in the range of ng L^{-1} to μg L^{-1} [55]. These concentrations are unlikely to cause acute effects in aquatic organisms (e.g., Refs. [56–58]). However, the continuous exposure (partially over the entire life cycle) of aquatic organisms inhabiting exposed stream reaches may induce chronic effects, such as changes in behavior, growth, and reproduction [59,60]. Accordingly, a meta-analysis at the scale of the USA [55] pointed to a medium to high risk of several PPCPs based on risk quotients (RQs). The RQs were calculated as the ratios of measured or predicted environmental concentrations and the predicted no-effect concentration, which is the concentration at which no adverse effect on aquatic organisms is expected, whereas the latter concentrations only included chronic toxicity values for fish. It is important to note that Deo [55] only considered a fraction (n = 93) of the total number of PPCPs used for human and livestock (>3000) [14]; therefore, the risk of PPCPs in the aquatic environment is not fully reflected. Accordingly, the answer to the question of how important PPCPs are for the biodiversity decline in aquatic ecosystems remains speculative [61], despite being listed as one of the biggest emerging threats for freshwater biodiversity [62].

In addition, antibiotic-resistant bacteria can overcome the inhibitory action of one or more antibiotics. Such resistances consequently diminish the success of infectious disease treatment, resulting in both important economic and societal consequences [63]. Wastewater treatment plants have been identified as one of the most important entry paths for antibiotic resistance from humans to freshwater environments [64] since the sewage entering the wastewater treatment plants combines the excreta and residues produced in the served area. Consequently, several studies (e.g., Refs. [65–67]) point to an increased tolerance of microbial communities downstream of wastewater treatment plants. Briefly, shifts in the community composition to more tolerant species, when comparing downstream to upstream communities, may ultimately lead to shifts in ecosystem performance once tipping points are exceeded (e.g., Refs. [68–70]). From the precautionary principle point of view, society should already act now to reduce the influx of PPCPs to streams and rivers, thereby safeguarding the integrity of such ecosystems.

Pharmaceuticals and personal care products in the aquatic environment — potential options to counteract

A reduction of PPCP surface water concentrations seems to be a sensible measure to reduce the potential for biodiversity effects and the development of PPCP resistance over the long term. To achieve this goal, we see several leverage points that will help to manage and control PPCP occurrence in the environment. The first opportunity for minimizing PPCP contamination and environmental risks is at the consumer level, with respect to (i) fewer prescriptions; (ii) reduced disposal of unwanted or leftover PPCPs through the sink, toilet, or garbage; and (iii) reduced meat consumption, which reduces the application of pharmaceuticals and growth promoters in livestock (Figure 2).

Antibiotics, for example, are a group of pharmaceuticals that are an indispensable and central pillar in medicine since their discovery in the late 1920s [71]; however, antibiotic resistance is a major and increasing global concern. Given that antibiotics can be considered a finite resource and only few new antibiotics are developed nowadays, existing antibiotics must be used more responsibly to guarantee their medical benefit over the long term. One of the WHO's cornerstones in the strategy for the containment of antimicrobial resistance from 2001 is to address unnecessary and incorrect use of antibiotics to maximally slow down the spread of antibiotic resistance [72]. In this context, Sweden could be seen as a role model on the European scale, given the early action in the mid-1990s to initiate long-term and structured measures on both the local and national level. Within the Swedish healthcare system, data for continuous resistance surveillance are being generated by relatively frequent sampling of infected patients and the culturing of obtained samples. Furthermore, treatment recommendations for common infections in outpatient care are in place that resulted in a sustained decrease in antibiotic consumption. These measures helped in keeping the level of antimicrobial resistance among the lowest within Europe [73].

Regarding the disposal of unwanted or leftover PPCPs, Wieczorkiewics et al. [74] showed that a substantial share of PPCP users disposed their medication in the household garbage (59% of respondents) or flushed them down the toilet and sink (31%). Strikingly, the majority of users (>80%) never received information about proper disposal. Therefore, public education on proper PPCP disposal is urgently needed. Furthermore, the increasing global demand for animal protein is predicted to significantly affect the antibiotic use in livestock up to ∼106 kt (67% increase compared to 2010 51), of which a share will ultimately end up in surface waters due to the use of manure as fertilizer. This poses a risk for a decline in freshwater biodiversity in general, as well as the development of antimicrobial resistance in particular (Figure 1) [75]. Consequently, reducing global demand for animal protein, such as through lower meat intake or personal consideration of vegetarian or vegan diets, would contribute to mitigating environmental risks associated with livestock production and farming (Figure 2).

Another way of controlling PPCPs at their source is addressing the waste produced by pharmaceutical industries and hospitals. Studies showed consistently higher levels of some PPCPs in effluents of pharmaceutical formulation facilities and hospitals than those in urban effluents with which those effluents were mixed, indicating that pharmaceutical formulation facilities and hospitals are one of the main sources of particular PPCPs (Figure 1) [53,76]. Small-scale, onsite facilities that enable a pretreatment of hospital wastewater before being discharged into the municipal wastewater system would help to reduce levels of certain PPCPs and counteract antimicrobial resistances. In addition, pharmaceutical industries could receive (financial) incentives to manufacture green pharmaceuticals [77], which are more prone to degradation after consumption and are safer for the environment [78].

Furthermore, advanced treatment techniques applied during wastewater treatment, such as oxidation with ozone and the application of granular activated carbon (GAC), showed promising results (Figure 2). Ozonation has shown a high potential for the oxidation of PPCPs in wastewater [79,80], with doses of 5–15 mg ozone L^{-1} leading to a complete disappearance of most of the assessed PPCPs. However, ozonation may only result in partial oxidation of PPCPs, resulting in biologically still active oxidation products. Nevertheless, studies on ethinylestradiol and carbamazepine [81,82] reported that partial oxidation was sufficient to significantly reduce the toxicological potential of the PPCPs. In a similar manner, the application of GAC showed up to 99% reductions in PCPP loadings in wastewater treated in a plant equipped with a full-scale GAC treatment facility [83].

Finally, as for pesticides, the application of constructed wetlands showed great potential for the removal of human and veterinary PPCPs from wastewater effluents (Figure 2). Constructed wetlands reduce the load of PPCPs mostly through biodegradation (aerobic and anaerobic), often in direct conjunction with further processes such as (ad)sorption to soil particles, direct plant uptake, and photodegradation [84,85]. Using these processes, up to 93% and 98% of the most widely studied human and veterinary PPCPs were reported to be removed [84,86,87]. However, the effective removal of PPCPs in constructed wetlands requires an integrated design that ensures biodegradation by using substrate material with high adsorption capacity, abundance of organic matter, and a high surface area, which enhances the removal of PPCPs and ensures a good functioning and efficiency of the constructed wetlands.

Concluding remarks

This overview suggests that some measures are already available to reduce the loss of pesticides and PPCPs from different land uses to adjacent water bodies (Figure 2), with their efficiency being variable. However, a reduction in the application of pesticides without considering their ecotoxicological potential may be misleading. Achieving the goal as postulated in the post-2020 Global Biodiversity Framework might require rethinking and likely rebuilding of the current agricultural landscape and revising practices. For instance, enlarging buffer strips, that is areas not being sprayed by pesticides, around rivers and streams could further limit pesticide fluxes through spray drift and runoff [34]. It might be an option to use this area for organic farming or other purposes such as the development of a network of natural habitats. The latter could serve also as refugia for species in the landscape and, in particular, for organisms that can suppress pest species due to predation [88]. Such biological pest control measures could be supplemented by a more heterogeneous culturing of crops (Figure 2) with crop rotation, creating a more resilient agricultural production in case of insect pest outbreaks [89]. Synergistic effects could also be leveraged via the careful combination of aforementioned approaches. Drainage water management in the agricultural landscape has become more important in recent decades due to the seasonal oversupply or undersupply of water [90], an issue that will be further exacerbated due to climate change. Thus, establishing sufficient retention areas for drainage or runoff water would both improve water availability during arid times and provide degradation opportunities for pesticides as well as veterinary pharmaceuticals. In the case of human PPCPs, a combination of approaches seems suited to combat associated implications for biodiversity, ecosystem functions, and human health. It is self-evident that a reduction in prescription and use of pharmaceuticals in combination with a more sustainable, or at least wider known, waste collection scheme could reduce concentrations in and thus exposure of receiving water bodies. Decentralized pretreatments (e.g., ozonation) of wastewater might further reduce the release from hot spots such as hospitals, while the wide diversity of chemicals used in households might be ideally treated by means of end-of-pipe technologies, which treat wastewater before being released to the environment. Although being relatively well-framed challenges, addressing them in a reliable and scientifically sound manner remains a multi-level attempt balancing environmental, societal, and economic interests, requiring, for sure, thinking outside of current boxes backed by scientific support and appropriate resources. Against the background of the entire arsenal of chemicals employed for various purposes, which has clearly outpaced our ability to predict or estimate environmental risks, an innovative strategy is required that allows us to reduce the diversity and amount of applied chemicals [2,91].

Author contributions

Conceptualization: M.B.; investigation: A.F. & M.B.; writing – original draft preparation, review & editing: all; visualization: A.F.; supervision: A.F.

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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.

Data availability

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

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