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Recommendations to reduce the streetlight effect and gray areas limiting the knowledge of the effects of plant protection products on biodiversity

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Abstract :

Preserving biodiversity against the adverse effects of plant protection products (PPPs) is a major environmental and societal issue. However, despite intensive investigation into the ecotoxicological effects of PPPs, the knowledge produced remains fragmented given the sheer diversity of PPPs. This is due, at least in part, to a strong streetlight effect in the field of ecotoxicology. Indeed, while some PPPs have been investigated in numerous ecotoxicological studies, there are many for which the scientific literature still has little or no information on their ecotoxicological risks and effects. The PPPs under the streetlight include a large variety of legacy substances and a more limited number of more recent or currently-in-use substances, such as the herbicide glyphosate and the neonicotinoid insecticides. Furthermore, many of the most recent PPPs (including those used in biocontrol) and PPP transformation products (TPs) resulting from abiotic and/or biotic degradation are rarely addressed in the international literature in the field of ecotoxicology. Here, based on a recent collective scientific assessment of the effects of PPPs on biodiversity and ecosystem services in the French and European contexts, this article sets out to illustrate the limitations and biases caused by the streetlight effect and numbers of gray areas, and issue recommendations on how to overcome them.

Keywords : Biases, Biopesticides, Collective scientific assessment (CSA), Contaminants of emerging concern (CECs), Currently used pesticides, Ecosystems, Transformation products

Preserving biodiversity against environmental contamination by plant protection products is still a scientific and regulatory challenge

The preservation of biodiversity has become a key objective for ensuring sustainable development, and human and animal health and well-being. The Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES 2019) recognizes chemical pollution as one of the five main drivers of biodiversity loss. Recent studies find alarming evidence that environmental contaminants (including chemicals) are part of a wider threat to our planet (Groh et al. 2022), and that the increasing diversity and quantities of anthropogenic contaminants jeopardize the safe operating space of several planetary boundaries (Persson et al. 2022). Plant protection products (PPPs), often simply called "pesticides," have long been identified as environmental contaminants contributing to the decline of biodiversity in both terrestrial and aquatic ecosystems (Carson 1962; Geiger et al. 2010; Beketov et al. 2013). Faced with this situation, the EU has decided to strengthen the legislation on the use of PPPs, to guarantee a higher level of protection of the environment. However, despite the adoption in 2009 of dedicated EU legislation called the "Pesticides package" (Regulation (EC) No. 1107/2009; Directive 2009/127/EC; Directive 2009/128/EC; Regulation (EC) No. 1185/2009) repealing the previous Council Directive 91/414/EEC (1991) concerning the placing of plant protection products on the market, and the implementation of subsequent regulations (e.g., Commission Regulations (EU) No. 546/2011, 547/2011, 283/2013, and 284/2013; Regulation (EU) 2019/1381) requiring that PPPs shall not have any unacceptable effect on the environment (including biodiversity), there has still been only limited progress made on measuring and reducing the risks and impacts of PPPs on biodiversity (European Court of Auditors 2020; Helepciuc and Todor 2022). This EU-wide observation is applicable to most regions of the world, and is probably even more alarming in those where pesticide legislation is less restrictive. For example, many PPPs that have been withdrawn by the EU because of the risks they pose to human or environmental health (e.g., acetochlor, atrazine, clothianidin, thiamethoxam, imidacloprid) are still legally used in different countries such as the USA, Brazil, or China (Leenhardt et al. 2023). It is interesting to note that the U.S. Environmental Protection Agency (EPA) has recently initiated a major effort to improve the regulation of PPPs, giving more weight to the risk to endangered species (Stokstad 2023).

France arrived at a similar conclusion than the EU based on an analysis of the effectiveness of the first French national action plan (called "Ecophyto"; French Republic 2018) to reduce the uses, risks, and impacts of PPPs (Cour des Comptes 2019; Guichard et al. 2017). In this context, the French Ministries responsible for the Environment, for Agriculture, and for Research commissioned two French Research Institutes (INRAE and Ifremer) to conduct a collective scientific assessment (CSA) of the international scientific knowledge on the effects of PPPs (encompassing active substances, adjuvants, and co-formulants) and their transformation products (TPs) on biodiversity and ecosystem services. The CSA addressed all synthetic, natural, and biological products or agents used in agricultural and non-agricultural areas. To cover the entire field of the CSA, 46 experts representing 19 universities and research institutes (Pesce et al. 2021) were mobilized for nearly two years (2020–2022), producing a report based on more than 4500 international references (Mamy et al. 2022). The main conclusions of this CSA are available in various formats (Leenhardt et al. 2023; Pesce et al. 2023). In particular, they reveal that the contamination of agricultural areas by PPPs undoubtedly contributes (together with other anthropogenic stressors such as land-use change; Rigal et al. 2023) to the decline of certain biological groups, among which terrestrial and aquatic invertebrates as well as birds, with neonicotinoids, and pyrethroids appearing to be among the most impactful of the currently used PPPs.

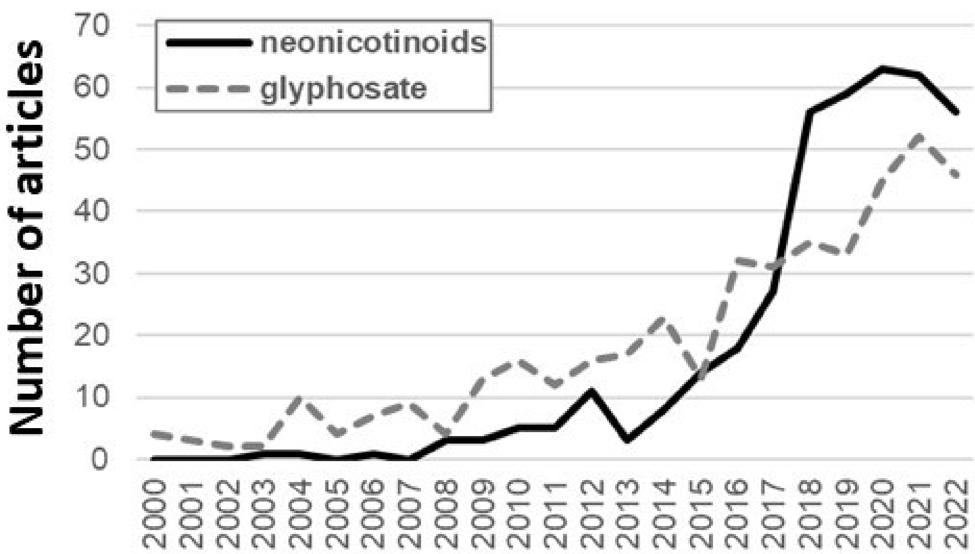
Unbalanced distribution of research and publication efforts in ecotoxicology precludes a reliable and exhaustive ranking of the most impactful PPPs for biodiversity

Besides providing an up-to-date state of knowledge, CSAs also crucially aim to identify uncertainties, controversies, and gaps in the scientific knowledge (INRA-DEPE 2018). Indeed, despite extensive literature dealing with the ecotoxicological effects of PPPs, the CSA concluded that the knowledge produced remains fragmented and incoherent given the diversity of these environmental contaminants. For example, in France, nearly 300 active substances are currently authorized as PPPs and marketed under about 1500 formulations containing co-formulants and adjuvants, to which we need to add an array of TPs as well as other PPPs that have been banned but are still present in the environment due to their persistence. Faced with this multitude of PPPs and the multitude of potential direct and indirect impacts on biodiversity, there are several drivers that determine the type of ecotoxicological data available in the relevant scientific literature. Some of these drivers can generate a "streetlight effect" that highlights certain substances, while for others, there is a great lack of published knowledge.

The "streetlight" and "in-vogue" effects make some PPPs more visible in the scientific literature

The "streetlight effect," which is observed in many scientific fields, primarily occurs when researchers search for knowledge "in the places where it is easiest to look" (Tsvetkov and Zayed 2021). Put simply, it is the tendency for researchers to select study cases mainly for reasons of convenience rather than broader scientific or societal relevance (Hendrix 2017). First of all, the types of results obtained in a study have limitations that are inherent to research tools (concepts, protocols, instruments, etc.) used. Research orientations and prioritizations can also be influenced by the "emblematic" nature of certain PPPs (e.g., glyphosate or neonicotinoids; Fig. 1) or organisms (e.g., bees or birds) or by the perception of their economic and/or societal usefulness (e.g., pollinators or predators of crop pests). This "emblematic" factor, which can sometimes be further fueled by targeted media coverage (or sometimes even overexposure in the media), may foster the establishment of stakeholder coalitions and increase demand for expertise or research incentives from public authorities, which in turns makes it easier for researchers to obtain dedicated funding (Vignati 2021).

***Fig. 1**: Number of articles found in Scopus (https://www.scopus.com ; 10 May 2023) year-by-year between 2000 and 2022 using the queries "TITLE-ABS-KEY (ecotox* AND neonicotinoid*)" (neonicotinoids) and "TITLE-ABS-KEY (ecotox* AND glyphosate)" (glyphosate)*



The most “popular” PPPs may therefore benefit from a kind of “in-vogue effect” (Borja and Elliott 2019) and thus become more extensively studied by the scientific community than the vast majority of other PPPs. This phenomenon, which some scientists see as a waste of research time and resources (Vignati 2021), can therefore compound the “streetlight effect” by adding a “magnifying effect,” i.e., the tendency to always single out the same PPPs as they are the most widely studied substances. This was nicely illustrated by Kristiansson et al. (2021), who assessed the year-by-year frequency of publications on over 3500 chemicals in over 130,000 scientific papers covering the period 2000–2019 and showed that just 65 of these chemicals accounted for half of all occurrences in the corpus studied. Interestingly, but ultimately disappointingly, the 10 PPPs they identified as the most commonly cited in the ecotoxicological literature were mainly legacy PPPs that have been banned for years in Europe (Table 1). The only substance in this list that is still currently authorized for use as a PPP is glyphosate, and the last substance to be banned was chlorpyrifos (Regulations (EU) 2020/17 and 2020/18). Surprisingly, no neonicotinoid substances appear in this list, despite the large number of ecotoxicological studies dealing with these PPPs (Mamy et al. 2023), but this may be due to the fact that the analysis performed by Kristiansson et al. (2021) considered each neonicotinoid insecticide individually (rather than as the broad term “neonicotinoids”, which is widely used in the scientific literature; Fig. 1).

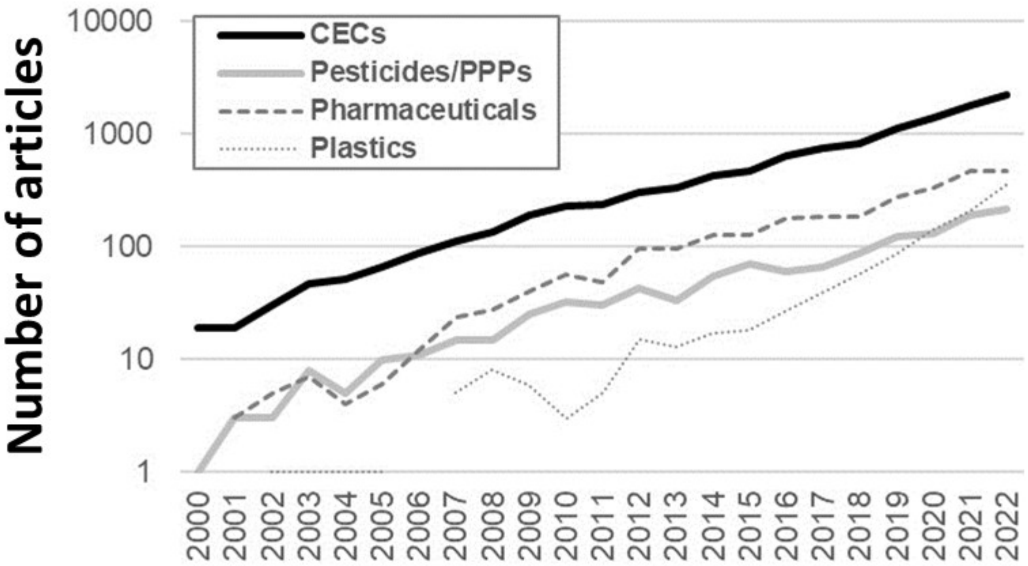
***Table 1**: List of the 10 PPPs most commonly cited in the ecotoxicological literature published between 2000 and 2019 (source: Kristiansson et al. 2021)*

Active substance	PPP family	Regulatory status in the EU (as a PPP)
Atrazine	Triazine herbicide	Banned in 2004 (2004/247/EC)
Chlorpyrifos	Organophosphate insecticide	Banned in 2020 (2020/17/EC and 2020/18/EC)
Clofenotane (DDT)	Organochlorine insecticide	Banned in the 1970s
Endosulfan	Organochlorine insecticide	Banned in 2005 (2005/864/CE)
Endrin	Organochlorine insecticide	Banned in the 1990s
Glyphosate	Organophosphate herbicide	Currently approved
Hexachlorobenzene	Organochlorine fungicide	Banned in the 1980s-1990s (dates vary between EU countries)
Lindane	Organochlorine insecticide	Banned in the 1980s–1990s (dates vary between EU countries)
Naphthalene	Insecticide	Banned in 2004 (2004/129/CE)
Pentachlorophenol	Organochlorine insecticide	Banned in 2003 (Commission Regulation (EC) No 2076/2002)

The “in-vogue effect” does not just concern individual PPPs (such as glyphosate, Fig. 1) or classes of PPPs (such as neonicotinoids, Fig. 1) but is also at work between different classes of chemicals. Kristiansson et al. (2021) showed that, from 2000 to 2019, the frequency of publications decreased significantly for ecotoxicological studies on PPPs (–23%) whereas it increased significantly for other classes of chemicals, the most striking example being that of pharmaceutical substances (+ 65%). This observation may echo the notion of “contaminants of emerging concern” (CECs), also called “emerging contaminants,” which are chemical or biological materials that are not commonly monitored in the environment but have the potential to contaminate it and for which environmental or public health risks are yet to be established (Naidu et al. 2016), although there is some variation in this definition between different authors (e.g., Sauvé and Desrosiers 2014; Yadav et al. 2021). Over the past 20 years, CECs have become a particularly attractive subject for research and an important source of funding within the scientific community.

CECs have thus grown into a fashionable on-trend research topic, as illustrated in Fig. 2 that shows the exponential increase in the number of scientific articles dealing with CECs (i.e., including the terms "contaminant*" and "emerging" in the article title, abstract or keywords; source: Scopus Database) from 2000 (19 articles per year) to 2022 (2224 articles per year), amounting to a total of 11,463 articles over this period. Among these articles, about 24% contained the term "pharmaceutical*" in the sections mentioned above (i.e., article title, abstract, or keywords) while less than 11% contained the terms "pesticide*" or "plant protection product*." Another striking illustration is the case of plastic contaminants (including nanoplastics and microplastics) that shows a marked increase in the year-by-year number of related publications from 2007 (five articles per year) to 2022 (365 articles per year) (Fig. 2).

***Fig. 2**: Number of articles found in Scopus (https://www.scopus.com ; 10 May 2023) year-by-year between 2000 and 2022 using the queries: (1) "TITLE-ABS-KEY (emerging* AND contaminant*)" (CECs); (2) "TITLE-ABS-KEY (emerging* AND contaminant*) AND (pesticide* OR (plant AND protection AND product*))" (pesticides/PPPs); (3) "TITLE-ABS-KEY (emerging* AND contaminant*) AND (pharmaceutical*)" (pharmaceuticals); and (4) "TITLE-ABS-KEY (emerging* AND contaminant*) AND (plastic* OR nanoplastic* OR microplastic*)" (plastics)*



Recommendations to broaden the scope of questions addressed in ecotoxicology

Researchers should be careful to avoid what Johnson et al. (2020) called the "bandwagon effect," i.e., re-demonstrating effects that have already been documented. Johnson et al. (2020) illustrated their point by mentioning the fact that over 250 articles document the ecotoxicological risks posed to fish by the synthetic estrogen medication ethinylestradiol. In a parallel example concerning PPPs, most of the numerous studies assessing the sublethal effects of neonicotinoids on honey bees are performed with only a limited number of worker phenotypes, whereas these effects are already known to be phenotype dependent (Tsvetkov and Zayed 2021). As previously asserted by Hanson et al. (2018), researchers should ask themselves whether their work and the expected results would contribute to improving the existing knowledge and addressing any identified gaps. This same questioning should include the choice of PPPs to study. Furthermore, building on the bibliometric analysis performed by Kristiansson et al. (2021), many scientists need to stop considering PPPs as "untrendy" contaminants. The PPP market is constantly evolving, as some substances or authorized uses get withdrawn while new ones and/or novel formulations come through the development pipeline.

Unpublished existing ecotoxicological data contribute to gray areas that make some PPPs less visible in the scientific literature

In contrast to the well-studied PPPs, there are many other PPPs for which the scientific literature has little or no information on their ecotoxicological risks and effects. For instance, the conclusions drawn by Kristiansson et al. (2021) corroborate the conclusions drawn by the CSA concerning the limited state of knowledge on ecotoxicological effects caused by most of the most recent PPPs (including biopesticides used for biocontrol; Pesce et al. 2023; Leenhardt et al. 2023). This observation, which is not limited to PPPs, is applicable to most of the environmental contaminants, including chemical pollutants registered in the EU or the USA (Johnson et al. 2020). However, it raises a recurring question: does the lack of publications really indicate a lack of research into these PPPs? Indeed, another very marked bias in ecotoxicology concerns the fact that published (or even publishable) articles generally report on studies that demonstrate significant ecotoxicological risks or effects (Wandal et al. 2007). Results that fail to show an effect (either because there is no effect or because the research design was unable to show the effect) get published less often than results that show an effect (Hanson et al. 2018). Furthermore, even if robust studies that report a lack of effects (i.e., “negative results”) manage to get published, they generally get cited less frequently than weaker studies that reported effects, which suggests that “negative-result” studies may be considered less interesting or relevant (Hanson et al. 2018). Regardless of whether these PPPs are not studied or simply do not make it into published papers, either way they are out of the “streetlight.”

Recommendations to reduce gray areas in PPP ecotoxicology

As mentioned above, it is challenging task to separate the “gray areas” (defined here as lack of published knowledge) left by the lack of ecotoxicological studies on certain PPPs from the “gray areas” left by the fact that knowledge exists but is not published or available to scientists. This makes it crucial to report all ecotoxicological studies and to make the resulting findings publicly accessible (Martin et al. 2019; Brock et al. 2021). This recommendation applies, among others, to the large sets of ecotoxicological data generated through the regulatory framework for the assessment of the impacts of PPPs before their placing on the market. While some of them are made easily accessible to scientists (e.g., in the EFSA Journal, which is an open access and online scientific journal that publishes the scientific outputs of the European Food Safety Authority), most of the datasets remain relatively confidential due to the difficulty of getting access to them. In the academic sphere, the researchers performing the studies need to make the effort to publish the data and/or make them findable, accessible, interoperable, and reusable following FAIR Guiding Principles (Wilkinson et al. 2016), but those who review submitted articles and the publishers (i.e., journal editors) also need to make the effort to promote the publication of well-conducted studies that report no (or not statistically significant) ecotoxicological effects (Hanson et al. 2018). The recent agreement on reforming research assessment, supported by the coalition for advancing research assessment (COARA 2022), proposes that the assessment of research, researchers, and research organizations should recognize the diverse outputs, practices, and activities that maximize the quality and impact of research. The changes in evaluation practices induced by this agreement should enable researchers to propose new ways to mobilize negative results on the effects of PPPs or other environmental contaminants for the benefit of both science and society.

Other specific challenges to be addressed in PPP ecotoxicology

The past few years have seen the development and rapid expansion of biocontrol products (commonly called biopesticides), based on the use of natural active substances, microorganisms, macroorganisms, or semiochemicals, which are viewed as environment-friendly alternatives to conventional PPPs (Amichot et al. 2018). The conclusions of the CSA highlighted a lack of scientific knowledge concerning the fate of biocontrol products in the environment and their ecotoxicological effects (Mamy et al. 2022; submitted; Pesce et al. 2023). Rare studies examined the contamination of the various environments (soil, water, sediment, and air) by biocontrol products, and they mainly concern the fate of Bacillus thuringiensis (Bt) proteins in the soil, which can persist from a few days to several years (e.g., Tetreau et al. 2012; Bruhl et al. 2020; Liu et al. 2021). Other works have also shown that certain natural (or identically synthesized) active substances used for biocontrol (e.g., abamectin, paraffin oil, spinosad, phosphonates) can persist in soils and water (Mamy and Barriuso 2022). In addition, the French National Agency for Food, Environmental and Occupational Health and Safety (Anses) identified abamectin as a high-priority substance for in-air monitoring due to its physical–chemical properties (Anses 2017), but such monitoring was not yet feasible due to analytical difficulties (Anses 2020). Besides contamination, the effects of biocontrol products have been under-investigated, whereas some substances, such as abamectin and spinosad, have been proved to be toxic for some non-target organisms, including bees, coccinelids, and earthworms (James 2003; Galvan et al. 2006; Kolar et al. 2008; Botina et al. 2020). Given that the development of biocontrol products is probably still in its infancy, environmental scientists (chemists and ecotoxicologists), environmental managers, and stakeholders are all advised to invest more effort in studying this class of PPPs in order to better characterize their fate in the environment, and their effects on terrestrial and aquatic ecosystems.

The main conclusions of the CSA also underlined the huge gap in knowledge on the environmental occurrence of TPs resulting from abiotic and/or biotic degradation of PPPs, and the resulting ecotoxicological risks and effects (Mamy et al. 2022; Pesce et al. 2023). There is a growing body of evidence to argue that environmental monitoring and risk assessment needs to better take account of TPs, as TP concentrations can exceed the concentration of their parent compounds, and TPs can prove more persistent, more mobile, and more toxic (Ji et al. 2020; Menger et al. 2021). The huge technological breakthroughs of the last decade in environmental chemistry, which has allowed the development and implementation of suspect and non-target screening approaches, now offer the possibility to detect and identify a wide range of PPP TPs that are still mostly unknown (Gonzalez-Gaya et al. 2021). Combined with the implementation of strategies that can serve to prioritize focal TPs to study (e.g., through the use of modeling, and in vitro and in silico analyses), these recent analytical capacities to monitor the environmental occurrence and fate of TPs represent a great opportunity to bring TPs under the "streetlight" (Storck et al. 2016; Hensen et al. 2020; Anagnostopoulou et al. 2022).

However, the scientific challenges and knowledge needed to provide a more exhaustive and generalizable overview of the impacts of PPPs on biodiversity involve more than PPPs used in biocontrol and PPP TPs. Many active substances—and chiefly most of those recently approved, as well as adjuvants and co-formulants—suffer from a lack of data that makes it hard to reliably monitor their environmental fate and associated ecotoxicological effects. In addition to these disparate levels of knowledge between different types of PPPs, the CSA conclusions highlighted disparate levels of knowledge between different types of organisms, environments, and territories (Pesce et al. 2023). Moreover, efforts to assess PPP effects on biodiversity still face the many technical and conceptual challenges encountered in ecotoxicology, which have been regularly mentioned in the literature over the past 20 years (e.g., Van Straalen 2003; Eggen et al. 2004; Bart et al. 2022).

These challenges include (but are not limited to) better consideration of (i) chemical mixtures (i.e., PPP mixtures or PPP–other chemical mixtures), including possible simultaneous or successive exposure, as frequently occurs in the environment; (ii) multiple stress scenarios, including extreme climate events that are occurring with increased frequency and intensity due to climate change; and (iii) indirect sublethal effects, through the study of biotic interactions. Sigmund et al. (2023) argued that it is essential to mobilize interdisciplinary skills (in the fields of ecotoxicology, ecology, environmental chemistry, modelling, and more) in order to overcome these challenges and help shape a better response to growing societal demands around biodiversity preservation and restoration.

Conclusions

Despite the extensive literature dealing with the ecotoxicological risks and effects of PPPs, the knowledge on their impact on biodiversity in terrestrial and aquatic ecosystems still has many "gray areas." This is partly because there are few if any published ecotoxicological studies on many PPPs. However, in some cases (which are difficult to identify and quantify), studies exist, but the resulting data is not published or not made available to the scientific community. This is why our first recommendation is to avoid conducting studies designed to demonstrate effects that have already been documented and validated by the scientific community, in order to explore new areas that are not currently under the "streetlight." Our second recommendation is to report all ecotoxicological studies, including those that fail to show an effect, and to make the resulting findings publicly accessible following FAIR Guiding Principles. Preserving biodiversity against the adverse effects of PPPs is still a major environmental and societal issue that remains on the agenda of many States, and so scientists and/or environmental managers and stakeholders need to stop considering PPPs as "untrendy" contaminants. We argue for a greater research effort not only on conventional currently used PPPs and their TPs, but also on biocontrol products, for which there is a pressing need to investigate further in order to confirm whether they are effectively environment-friendly alternatives to conventional PPPs. Some of these PPPs (especially biocontrol products and TPs) should probably be more explicitly recognized as CECs, which would make them a more attractive focus for research and funding within the scientific community.

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