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Policy Analysis

Enhancing Scientific Support for the Stockholm Convention's Implementation: An Analysis of Policy Needs for Scientific Evidence

Zhanyun Wang,* Sam Adu-Kumi, Miriam L. Diamond, Ramon Guardans, Tom Harner, Agustín Harte, Natsuko Kajiwara, Jana Klánová, Jianguo Liu, Estefania Gastaldello Moreira, Derek C. G. Muir, Noriyuki Suzuki, Victorine Pinas, Timo Seppälä, Roland Weber, and Bo Yuan

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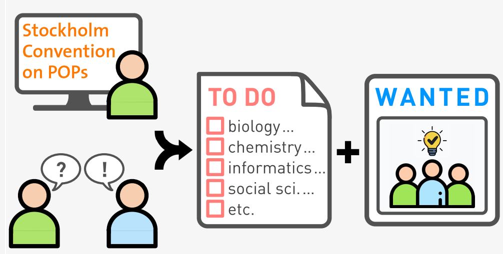
ABSTRACT: The Stockholm Convention is key to addressing the global threats of persistent organic pollutants (POPs) to humanity and the environment. It has been successful in identifying new POPs, but its national implementation remains challenging, particularly by low- and middle-income Parties. Concerted action is needed to assist Parties in implementing the Convention's obligations. This analysis aims to identify and recommend research and scientific support needed for timely implementation of the Convention. We aim this analysis at scientists and experts from a variety of natural and social sciences and from all sectors (academia, civil society, industry, and government institutions), as well as research funding agencies. Further, we provide practical guidance to scientists and experts to promote the visibility and accessibility of their work for the Convention's implementation, followed by recommendations for sustaining scientific support to the Convention. This study is the first of a series on analyzing policy needs for scientific evidence under global governance on chemicals and waste.



KEYWORDS: *science−policy interface, persistent organic pollutants, policy formulation, policy adoption, effectiveness evaluation, multilateral environmental agreements, hazardous substances*

1. INTRODUCTION

Anthropogenic chemical pollution is increasingly recognized as a global threat to humanity and the environment.[1−3] Complementing national and regional efforts,[4,5] the international community has come together with concerted action, with one major focus on hazardous chemicals that are transported across international boundaries via natural forces (wind, water currents, or migratory species) and/or via ever-intensifying global trade of resources, chemicals, goods, and waste.[6] In particular, several global multilateral environmental agreements (MEAs) and many more regional MEAs have been established to tackle specific international issues on chemicals and waste. Well-known global MEAs include the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade, the Stockholm Convention on Persistent Organic Pollutants, and the Minamata Convention on Mercury.

This study is the first in a series of papers that analyzes global MEAs on chemicals and waste, following in the spirit and recommendations of Klánová et al. (2011).[7] We examine the Stockholm Convention (hereafter referred to as "the Convention"),[8] which was adopted in 2001 and entered into force in 2004. The Convention's overall objective is to protect human health and the environment from persistent organic pollutants or POPs (Article 1), defined as chemicals with high persistence in the environment, bioaccumulation potential, adverse effects, and long-range environmental transport potential. As of November 2021, the Convention has 185 Parties comprising 184 countries and the European Union.

Here we highlight two key characteristics of the Convention. First, it embeds the Precautionary Principle of the Rio Declaration on Environment and Development (Article 1), that is, "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation". Second, the Convention is dynamic, including a process for regularly assessing and listing new POPs. The Convention initially covered the "dirty dozen" chemicals or groups of chemicals. As of 2021, 18 chemicals or

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groups of chemicals have been added (see Table 1), and seven more are under review, or are to be reviewed, for listing.

The mechanism for listing new chemicals represents a key aspect of the Convention in maintaining oversight of the ever-growing universe of chemicals on the global market and scientific knowledge. The recent listings (see Table 1) have generally shifted from "obsolete" pesticides to "in-use" industrial chemicals, including ones with myriad uses such as short-chain chlorinated paraffins (SCCPs) and perfluorooctanoic acid (PFOA), its salts and PFOA-related compounds. Some modeling studies have proposed hundreds or more chemicals on the market as potential candidates of POPs that need to be reviewed for listing.[9−11] Against this background, the Convention's implementation faces two significant challenges.

First, chemical-specific information[5] is generally lacking, impeding review and listing of new chemicals. The Convention has a predefined set of information that need to be considered in its multistep listing process (see Section 3 below). Despite flexibility included in Article 8, information that is deemed missing or inconclusive can delay the listing process. The latest example is Dechlorane Plus: the step of reviewing its risk profile has been extended for a year due to a lack of conclusive evidence of adverse effects.[12] Second, it is increasingly challenging for all Parties, particularly low- and middle-income ones, to compile an overview of POPs present within their national borders and transport via goods and waste, and to develop and implement effective control measures. For example, as of March 2021, over 70 Parties have not submitted their updated National Implementation Plans (NIPs) addressing chemicals listed since 2009.[13]

Concerted action is urgently needed to support the Convention's implementation in an efficient and timely manner.[14] Recognizing "the importance of strengthening the science−policy interface for the effectiveness of the conventions" (Decision SC-7/30), a joint "From Science to Action" initiative was launched in 2015 under the Basel, Rotterdam and Stockholm Conventions. A survey under this initiative identified several major science−policy gaps, including (1) data gaps and the lack of capacity to generate data in low- and middle-income countries, (2) the lack of national capacity to review and assess information, and (3) challenges in knowledge translation and making scientific information accessible to policy- and decision-makers.[15]

To address these gaps[16] and in line with the "From Science to Action" initiative, this analysis aims to engage the scientific community by identifying research and scientific support needed for timely implementation of the Convention (hereafter referred to as "policy needs for scientific evidence"). We aim this analysis at scientists and experts from a variety of natural and social sciences and from all sectors (academia, civil society, industry, and governmental institutions), as well as funding agencies.

We first provide a brief overview of the major policy development processes and actors under the Convention. Then, we discuss identified policy needs for scientific evidence related to the established processes, including timeframes of the policy windows, set out by the Convention's provisions and decisions. This analysis notes the interconnections between the Stockholm Convention and other global MEAs, many of which will be elaborated upon in the subsequent analysis of other global MEAs. Moreover, we investigate needs for scientific evidence that are not requested within the established processes but nevertheless are important for consideration for enhancing the Convention's effectiveness. All identified needs are summarized below, with background details of individual needs provided in the Supporting Information (SI); these needs are formulated at a general level without prioritization, and future studies are warranted to review the landscape of existing scientific evidence in respective fields and identify critical gaps. We further provide practical guidance on how scientists and experts may provide support to the Convention's implementation, followed by recommendations for sustaining scientific support to the Convention.

2. BACKGROUND ON POLICY DEVELOPMENT UNDER THE STOCKHOLM CONVENTION

2.1. Major Actors. The Conference of the Parties (COP), which comprises governments of the Parties (Article 19), evaluates and makes decisions on the Convention's implementation. The Secretariat runs the Convention's day-to-day operations as specified in Article 20 and as determined by COP, including information exchange, capacity building and technical assistance. In addition, several subsidiary bodies have been established to facilitate specific implementation areas, including the POPs Review Committee (POPRC), 16 Regional Centres, the Effectiveness Evaluation Committee, and five Regional Organization Groups in each UN region and the Global Coordination Group under the Global Monitoring Plan (GMP). The roles and responsibilities of these subsidiary bodies in the Convention's implementation are briefly described below; For more details, see Supporting Information (SI) Section S1.1.

2.2. Major Processes. The general policy development processes under the Convention are illustrated in Figure 1A, organized using a common five-stage framework:[17] agenda setting, policy formulation, policy adoption, policy implementation, and policy evaluation. Key actors and thus recipients of scientific evidence can be different in individual stages, and are further elaborated in Section 6 below.

As a general starting point (i.e., agenda setting stage), a Party may propose a chemical for listing (Article 8), an amendment of the Convention's text (Article 21), or the adoption and amendment of annexes (Article 22). Proposals related to Articles 21 and 22 will directly be discussed by COP at its next meeting, whereas proposals for a new listing will first trigger a predefined three-step scientific assessment process by POPRC (i.e., policy formulation stage).

The three steps for assessing a new chemical are screening, risk profile, and risk management evaluation, taking at least three meetings/years to conclude (when facing no extension of individual steps). The screening takes place in the same year as the nomination (if the deadline is met); the proposal advances to the next step if POPRC agrees that the chemical meets the screening criteria set in Annex D. Then, POPRC prepares a draft risk profile intersessionally, following information requirements set out in Annex E (note that this is not a risk assessment). At its next meeting, if POPRC agrees that "the chemical is likely as a result of its long-range environmental transport to lead to significant adverse human health and/or environmental effects such that global action is warranted", the proposal moves forward. Subsequently, POPRC prepares a draft risk management evaluation intersessionally, focusing on control measures and socio-economic aspects as set by Annex F. At a third meeting, POPRC finalizes the risk management evaluation and makes recommendations to COP on listing in

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Table 1. An Overview of Chemicals Listed under the Stockholm Convention on POPs[a]

year added	chemicals	uses	annex	current time-limited specific exemptions (SE) and/or time-unlimited acceptable purposes (AP)[b]
2001	aldrin	P	A	none
	chlordane	P	A	none
	dichlorodiphenyltrichloroethane (DDT)	P	B	AP: disease vector control, as specified
	dieldrin	P	A	none
	endrin	P	A	none
	heptachlor	P	A	none
	mirex	P	A	none
	toxaphene	P	A	none
	hexachlorobenzene (HCB)	P	A + C	none
	polychlorinated biphenyls (PCBs)	I	A + C	SE: articles in use, as specified
	polychlorinated dioxins/furans (PCDD/Fs)	N.A.	C	none
2009	α-/β-hexachlorocyclohexane (HCH)	P	A	none
	chlordecone	P	A	none
	lindane	P	A	none
	hexabromobiphenyl (HBB)	I	A	none
	commercial octabromodiphenyl ether (BDE) (hexa- and heptaBDEs)	I	A	SE: recycling of articles, as specified
	commercial pentaBDE (tetra- and pentaBDEs)	I	A	SE: recycling of articles, as specified
	pentachlorobenzene	I + P	A + C	none
	perfluorooctanesulfonic acid (PFOS), its salts and perfluorooctanesulfonyl fluoride (PFOSF or POSF)	I + P	B	AP: insect baits for agricultural control of leaf-cutting ants, as specified; SE: closed-loop hard-metal plating, fire-fighting foam for Class B fires, as specified
2011	technical endosulfan and related isomers	P	A	SE: crop-pest complexes, as specified
2013	hexabromocyclododecane (HBCD or HBCDD)	I	A	SE: expanded or extruded polystyrene in buildings, as specified
2015	pentachlorophenol (PCP), its salts and esters	I + P	A	SE: utility poles and cross-arms, as specified
	polychlorinated naphthalenes (PCNs)	I	A + C	SE: production of polyfluorinated naphthalenes
	hexachlorobutadiene (HCBD)	I	A	none
2017	HCBD	I	C	none
	commercial decaBDE	I	A	SE: parts for use in vehicles, aircraft, textile products, additives in plastic housings and parts, polyurethane foam for building insulation, as specified
	short-chain chlorinated paraffins (SCCPs)	I	A	SE: additives in transmission belts, rubber conveyor belts, leather, lubricant additives, tubes for outdoor decoration bulbs, paints, adhesives, metal processing, plasticizers, as specified
2019	dicofol	P	A	none
	perfluorooctanoic acid (PFOA), its salts and PFOA-related compounds	I	A	SE: photolithography or etching processes in semiconductor manufacturing, photographic coatings applied to films, textiles for the protection of workers, invasive and implantable medical devices, fire-fighting foams, production of perfluorooctyl bromide for the production of pharmaceuticals, manufacture of polytetrafluoroethylene (PTFE) and polyvinylidene fluoride (PVDF) in membranes, heater exchangers and industrial sealants, manufacture of polyfluoroethylene propylene (FEP) in high voltage electrical wire and cables, manufacture of fluoroelastomers in o-rings, v-belt and car interior, as specified

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Table 1. continued

[a]P = pesticidal uses; I = industrial uses; N.A. = not applicable; Annex A = elimination; Annex B = restriction; Annex C = unintentional production. [b]As of August 2021. Here the description of individual specific exemptions (SE) and acceptable purposes (AP) have been condensed. For some POPs, additional SE and/or AP existed in the past, which are no longer available (1) in accordance with the decisions by the Conference of the Parties (COP), or (2) in accordance with Article 4 of the Convention, when there are no longer any Parties registered for a particular type of specific exemption, no new registrations may be made with respect to such exemptions. For details on individual SEs and APs, including past ones, please consult the Convention's Annexes.[8] In addition, several additional exemptions exist under the Convention; for details, see SI Section S1.2.1.

Annexes A (elimination), B (restriction), and/or C (unintentional production). POPRC can also recommend specific use(s) of the chemical and related production to be exempted from the Convention's control measures, mainly in the form of either time-limited "specific exemptions" (up to 5 years if not defined otherwise, with possible extension of another 5 years if agreed by COP) or time-unlimited "acceptable purposes". During the three assessment steps, all Parties and observers to the Convention are invited to submit information and comments through calls issued by the Secretariat.

At its biennial meeting (since 2007), COP makes decisions based on the proposal(s) and POPRC's recommendations, generally through consensus among Parties (i.e., policy adoption stage). COP also considers any additional information presented at the meeting, and may therefore reach decisions deviating from the original proposal or POPRC's recommendations (e.g., with more or less exemptions). Parties can have different entry-into-force dates for implementing COP's decisions due to varied arrangements for ratification (for details, see SI Section S1.2.2).

Upon entering into force for a Party, the Party has obligations to implement the decisions through national (or regional) legislation. Currently, the Parties' legal obligations include: taking measures to reduce or eliminate POP releases from intentional production and use (Article 3), from unintentional production (Article 5), and from stockpiles and waste (Article 6); registering specific exemptions and acceptable purposes if relevant (Article 4, Annexes A and B); developing, reviewing and implementing its NIP (Article 7); facilitating or undertaking information exchange (Article 9); promoting and facilitating public information, awareness and education, within their capabilities (Article 10); encouraging and/or undertaking research, development, monitoring and cooperation pertaining to POPs, within their capabilities (Article 11); and cooperating to provide timely and appropriate technical assistance to low- and middle-income Parties (Article 12). To assist national implementation, the Secretariat, together with experts, develops and updates tools, including guidance on establishing NIPs, national inventories, control measures such as best available techniques (BAT) and best environmental practices (BEP) for unintentional POPs and the use of certain chemicals listed in Annexes A and B, and alternatives.[18] In addition, the Regional Centres develop and implement technical-assistance, capacity-building and technology-transfer projects in the (sub)region.[19]

Various mechanisms exist for evaluating the effectiveness of existing measures (i.e., policy evaluation stage). At the national level, Parties shall regularly review and update their NIPs (Article 7) including the action plan to address POPs listed in Annex C (Article 5), review their continuing need for specific exemptions if any (Article 4), and report implementation measures and their progress (Article 15).

At the global level, following a six-year cycle (current one: 2018−2023), COP evaluates how the Convention is approaching its objective, determines the effectiveness of specific measures, and identifies ways for improvement (Article 16), mainly through work under the GMP and the effectiveness evaluation framework (for details, see SI Sections S1.2.3 and S1.2.4).

The GMP serves as a harmonized framework for collecting comparable monitoring data on the presence of POPs, in order to identify changes in their concentrations over time, as well as on regional and global environmental transport. All the data

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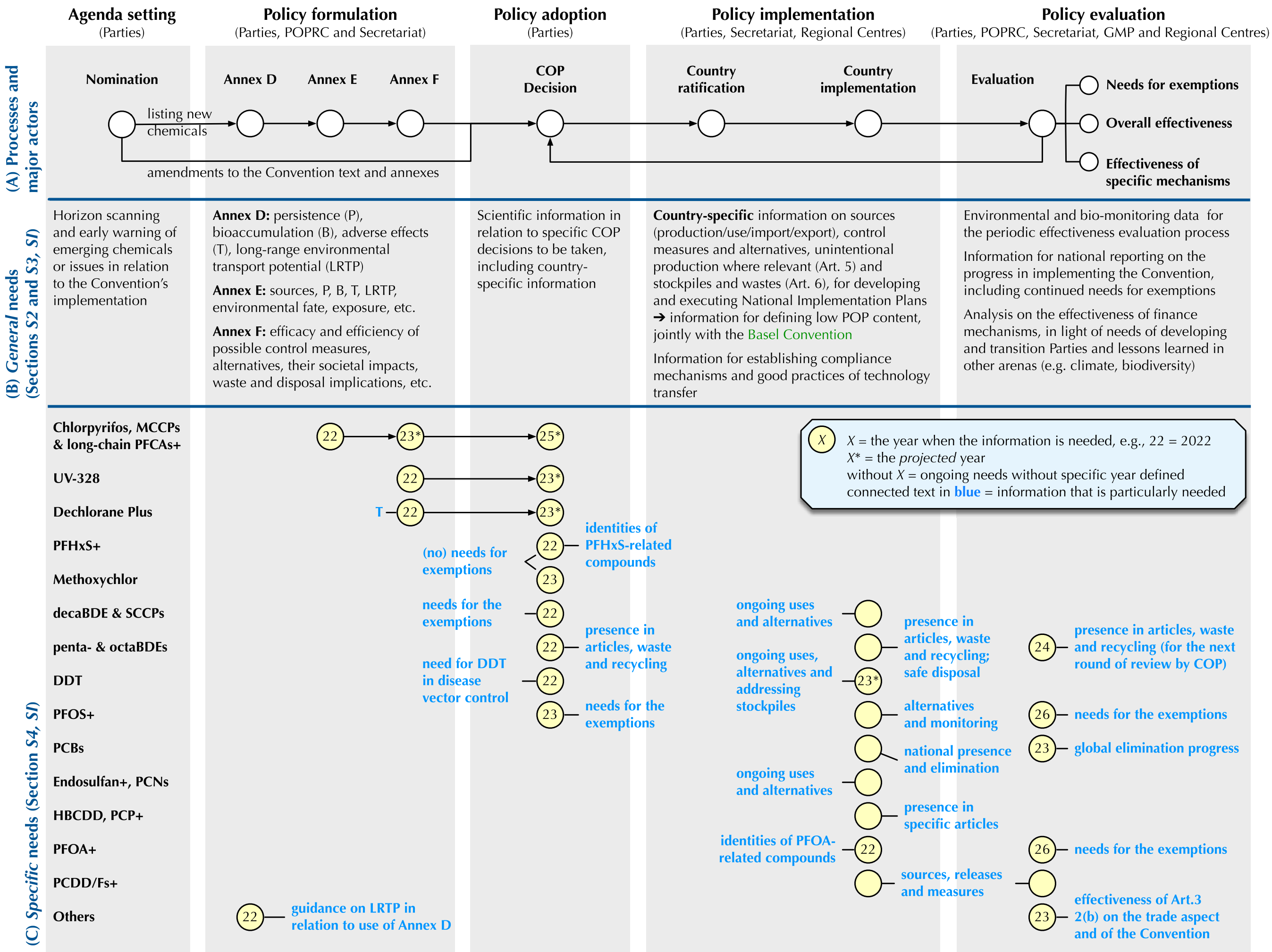

Notes: ***decaBDE*** = deca-brominated diphenyl ether; ***endosulfan+*** = endosulfan and its related isomers; ***HBCDD*** = hexabromocyclododecane, also under the acronym "HBCD" under the Convention; ***MCCPs*** = medium-chain chlorinated paraffins; ***PCBs*** = polychlorinated biphenyls; ***PCDD/Fs+*** = polychlorinated dioxins/furans and other unintentional persistent organic pollutants; ***PCNs*** = polychlorinated naphthalenes; ***PCP+*** = pentachlorophenol, its salts and esters; ***penta- & octaBDEs*** refer to commercial pentaBDE and octaBDE mixtures, which also contain other BDE congeners; ***PFCAs+*** = perfluoroalkylcarboxylic acids, their salts and related compounds; ***PFHxS+*** = perfluorohexanesulfonic acid (PFHxS), its salts and PFHxS-related compounds; ***PFOA+*** = perfluorooctanoic acid (PFOA), its salts and PFOA-related compounds; ***PFOS+*** = perfluorooctanesulfonic acid (PFOS), its salts and PFOSF; ***SCCPs*** = short-chain chlorinated paraffins

Figure 1. Overview of the general workflow, as well as the general and specific needs for scientific evidence identified in this study, under the Stockholm Convention.

are publicly available via the GMP data warehouse (www.pops-gmp.org) or other program databases. Also following a six-year cycle, these data are synthesized and analyzed by the Regional Organization Groups and the Global Coordination Group. As of August 2021, two series of regional and global monitoring reports and the five regional reports of the third series have been published,[20] and the third global monitoring report is being prepared.

The effectiveness evaluation framework defines the baseline, and elements and indicators to be evaluated. Under the framework, the evaluation is conducted during the last two years of the six-year cycle. First, the Secretariat compiles information gathered through existing arrangements under the Convention such as GMP monitoring reports and national reporting. This compiled information is then made available to the Effectiveness Evaluation Committee to prepare an assessment report, including conclusions and recommendations, for COP's consideration.

There are also other evaluation processes under the Convention, including the review process for entries in the registers of specific exemptions (Decisions SC-3/3, SC-4/3, and SC-7/1), review of the continued need for exemptions and progress made in the elimination of certain chemicals such as PCBs, PBDEs, DDT, PFOS, its salts and PFOSF, and the review of financial mechanisms (Article 13).

3. NEEDS FOR SCIENTIFIC EVIDENCE SET BY THE CONVENTION'S PROVISIONS AND DECISIONS

3.1. General Needs. These are ongoing policy needs without reference to specific individual chemicals or implementation mechanisms (see Figure 1B), and are detailed in SI Section S2.

At the agenda-setting stage, a major need is to identify *which chemicals may have POP characteristics* and to inform Parties for considering their nomination (this also helps countries in fulfilling the requirements according toparagraphs 3 and 4 of Article 3). Such horizon scanning and early warning by the scientific community is warranted on a regular basis, and may start with the following approaches: (1) using in silico models to screen chemicals on the global market and their transformation products,[9−11,21] (2) targeted, nontargeted or suspect screening of chemicals present in remote environments and biota,[22] and (3) reviewing emerging POP-related empirical

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evidence such as persistence, mobility and long-range transport, bioaccumulation, adverse effects, and environmental monitoring.[23]

An important need here is not only the use of, but also improving these approaches.[24] First, the applicability domain of in silico models needs to be continuously examined and improved to ensure coverage. This includes expanding the training sets of existing models (e.g., by strategically selecting chemicals not covered by empirical testing)[25] and developing new models to cover additional aspects (e.g., bioaccumulation models that include additional mechanisms such as protein-binding for ionizable compounds like PFOA).[26] Also, the knowledge base upon which properties qualify a chemical as a POP needs to be regularly reviewed to inform model development. Second, in addition to ongoing methods development such as improving data processing workflows,[27] concerted effort is warranted to reveal and compile the structural identities of chemicals on the market to enable suspect screening.[28] Such efforts include revealing chemicals that are registered as confidential business information, polymers, and UVCBs (substance of unknown or variable composition, complex reaction products, or biological materials), as well as identifying those occurring unintentionally such as manufacturing byproducts, unreacted intermediates, and transformation products.[5,29−33] Such efforts may include screening commercial products,[34,35] compiling existing information scattered in the public domain,[5] and exploring ways to make company-registered information (e.g., through the premanufacture notice in the United States, pursuant to 40 CFR § 720.45) publicly accessible. Third, a dedicated knowledge base can be built up to capture scattered POP-related empirical evidence in a timely manner as it emerges, similarly to recent knowledge base development for endocrine disrupting chemicals.[36]

At the policy-formulation and -adoption stages, a major need for scientists is to provide *POPs-related information required by the Convention, from hazardous properties (Annexes D and E), to sources and exposure (Annex E), to control measures and alternatives (Annex F)*. Maintaining adequately funded POP-related research including monitoring is needed here to allow strategic buildup of such information, in line with Article 11 of the Convention. This need arises as a chemical may suddenly be nominated with relatively short time windows for generating and providing relevant information to inform POPRC and COP. Further, while information requirements specified in the Annexes allow for flexibility in most aspects (e.g., no predefined (eco)toxicological end points), they have constraints in some other aspects (e.g., determination of bioaccumulation potential based on measured values). Hence, we highly recommend that readers consult SI Sections S2 and S3 for the information requirements laid out in the Annexes and considerations by POPRC for assessing new chemicals thus far and regularly check the latest development of assessment guidance from POPRC.

At the policy-adoption, -implementation and -evaluation stages, *country-specific baseline information on sources, exposure, control measures and alternatives* becomes critical so that Parties can develop their own position for COP negotiations,[37] develop and implement NIPs (Article 7),[38] and conduct national reporting (Article 15), respectively.

It is important to note that often Parties lack country-specific baseline information and especially low- and middle-income ones also lack the necessary capacity (including basic analytical capacity) to generate such information.[39,40] Here the scientific community can and should play a key role. For example, in cooperation with the Regional Centres, scientists can assist individual Parties, tailored to their conditions and needs, in establishing national inventories, evaluating needs for specific exemptions, developing and implementing suitable strategies, control measures and legislation, transitioning to safer alternatives (including nonchemical alternatives),[41] promoting BAT/BEP, identifying and supporting the cleanup of contaminated hotspots including stockpiles and waste, conducting environmental and biomonitoring that complements the GMP, and establishing domestic capacities and capabilities to conduct the aforementioned activities.

In addition to field activities in specific countries, advancing generic methods is needed for estimating global production, use and emissions, as well as cost-effective and transferable analytical methods for evaluating presence or trends.[42] Socio-economic studies that investigate social, environmental and public health benefits for Parties when addressing POPs are warranted to foster political commitment and action.[43,44] Furthermore, several recent listings refer to groups of POPs using a descriptive definition that may be ambiguous for nonchemists/experts when implementing the Convention (e.g., SCCPs defined as "straight-chain chlorinated hydrocarbons with chain lengths ranging from C_{10} to C_{13} and a content of chlorine greater than 48 per cent by weight"). As more group listings will occur (e.g., perfluorohexanesulfonic acid (PFHxS) and related compounds), the scientific community can help to develop easy-to-use cheminformatics tools. Such tools could automatically digest chemical structural information and highlight whether a substance is included in the listing or not, as well as aid in compiling databases/lists that contain already identified substances (note that POPRC is preparing an indicative list of substances covered by the listing of PFOA, its salts, and PFOA-related compounds).[45−47]

At the policy-implementation stage, the Convention must define the low POP content thresholds for individual POPs in end-of-life products. These thresholds are used to distinguish POP-containing wastes that must be disposed in an environmentally sound manner (Article 6). We do not expand on this here as such work is conducted under the framework of technical guidelines for POP wastes under the Basel Convention (this will be analyzed in a future analysis of the Basel Convention).

In addition to the aforementioned POPs-related activities, the scientific community can support individual implementation mechanisms under the Convention such as information exchange (Article 9), and can contribute to public information, awareness and education (Article 10). In addition, comparative studies can investigate compliance mechanisms under different MEAs, including those outside the field of chemicals and waste, with the purpose of identifying good practices and lessons learned to inform policymakers regarding establishing compliance mechanisms (Article 17) and evaluating financial mechanisms (Article 13).

3.2. Specific Needs. These are policy needs related to specific chemicals or implementation matters, often with known or predictable policy time windows (see Figure 1C). Below is a brief overview of the needs; readers are highly recommended to check SI Section S4 for details on individual needs (including the corresponding Convention's decisions and existing discussion).

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Currently, POPRC is assessing or will assess the following substances, requiring timely generation and synthesis of scientific evidence required by Annexes D−F: chlorpyrifos (risk profile), chlorinated paraffins with carbon chain lengths in the range C_{14-17}, and chlorination levels at or exceeding 45% chlorine by weight (i.e., medium-chain CPs or MCCPs; risk profile), long-chain perfluoroalkylcarboxylic acids (PFCAs), their salts and related compounds (risk profile), Dechlorane Plus (risk management evaluation), and UV-328 (risk management evaluation).[12,48]

Country-specific baseline information is much needed for many individual POPs at the policy-adoption, -implementation, and -evaluation stages, with varied foci and time windows highlighted in Figure 1C. Upcoming needs for scientific evidence for COP's consideration are related to the listing of PFHxS, its salts and PFHxS-related compounds and methoxychlor, and examining the continued needs of exemptions for BDEs, SCCPs, and DDT at the next COP meeting in June 2022, as well as examining the continued needs of exemptions for PFOS, its salts and PFOSF at the COP meeting in 2023. Here, information gaps are country-specific scientific, technical, environmental and economic information on current production, use, presence in articles, trade, disposal, recycling, and alternatives remains a major gap, as shown in the reports on BDEs and SCCPs presented at the 16th POPRC meeting in 2021.[12] A further need is an information synthesis on a global scale to gauge progress toward global elimination of PCBs and global minimization of PCDD/Fs.

Two process-related, specific needs have also been identified. One need is related to the effectiveness evaluation of trade control, specifically regarding the current procedure as set in the paragraph 2(b) of Article 3. Socio-economic studies are warranted to support this effectiveness evaluation, including consideration of the link of the Stockholm Convention to the Basel and Rotterdam Conventions.

The other need is for better understanding mechanisms of long-range environmental transport of chemicals.[12] While the Convention has listed chemicals that may undergo long-range environmental transport via natural particles (such as decaBDE),[49] plastic particles as a carrier has not been previously considered and requires further evaluation.[50] Questions were raised at the 16th POPRC meeting during the assessment of UV-328—a plastic additive,[12] including how much is transported via plastic particles to a remote region and then is accumulated by biota, the magnitude of this route relative to other transport pathways, and how geographical heterogeneity of plastic-particle transport impacts the long-range environmental transport of chemicals therein.

To advance this discussion, POPRC has started to prepare a document on application of the Annex D criteria for assessing long-range environment transport of chemicals. Although a large body of scientific evidence has been amassed, areas requiring more work will be identified. Thus, this document under development can serve to inform future studies.

Meanwhile, two matters warrant careful consideration in future studies on chemical transport via plastics. First, chemical additives need to be distinguished from unintentional chemicals that are accumulated by plastics from the environment, as the former are most often present in plastics at levels that are orders of magnitude higher[51−54] than the latter.[55] This distinction is needed to distinguish between plastics that are a source of chemicals to biota rather than plastics that are a sink.[56−59] Second, the inter-relationship between the polymer matrix and additives is critical to consider, as it may influence multiple factors such as maximum adsorption capacity of the polymer matrix, release potential of the additives from the polymer matrix,[60,61] and fragmentation and density, and thus transport distance of the plastic particles.[62,63]

4. ADDITIONAL SCIENTIFIC EVIDENCE NEEDED FOR FUTURE CONSIDERATION

Through a literature review and consulting with experts, we have identified further needs for scientific evidence that are not directly requested by the existing processes under the Convention, but are nevertheless important for consideration to improve the Convention's effectiveness. This analysis accounts for outcomes of the Convention's official effectiveness evaluation (see SI Sections S5−S7).

4.1. Expanding the Scope of Chemical Grouping. Two group-listing approaches have been taken under the Convention, that is, grouping of congeners (e.g., PCBs, PCNs, PCDD/Fs) or isomers (e.g., hexachlorocyclohexane, endosulfan), and grouping of precursors and transformation end products (e.g., PFOA and related compounds). Future studies may investigate how to expand the approaches in order to allow for more efficient listing of POPs that are structurally similar (e.g., approaches to simultaneously listing substances like PFOS, PFOA, PFHxS, and long-chain PFCAs to avoid undergoing four assessment and listing cycles as is the case now).[64] For example, online cheminformatics tools and databases may be developed that can automatically screen chemicals on the market and identify ones that are structurally similar to the target compound(s) (e.g., homologous series) to inform grouping.[65] Such approaches may also be integrated by the Parties into their national chemical registration frameworks to prevent structurally similar POP candidates from entering the market in the first place, in line with paragraph 3 of Article 3 of the Convention (see SI Section S2I).

4.2. Transition to Safer Alternatives. At least two aspects warrant concerted efforts from the scientific community. First is the identification of safer alternatives in order to avoid regrettable substitution of POPs by substances that are later identified as POPs (e.g., decaBDE) or POP candidates (MCCPs). Many alternative assessment frameworks have been developed.[66,67] Building on these assessment frameworks, future studies may investigate ways to foster transitions going beyond readily available "drop-in" chemical alternatives, including starting with fundamental consideration of the function(s) of POPs in a given use and the actual needs to replace them (e.g., direct phase-out without substitution may be most sensible when this function is not needed).[68−70] Novel approaches, such as function-based groupings of chemicals, may also be investigated as ways to identify safer alternatives by looking beyond structurally similar chemicals when a chemical function in a given use is currently needed.[41,54]

Second, low- and middle-income Parties need access to alternatives.[71,72] The scientific community may help the Parties on this matter in the following two ways: (1) mapping and informing on good practices of international technology transfer (e.g., under other MEAs) for establishing possible mechanisms under the Convention that would allow the Parties to gain access to existing alternatives from other Parties, and (2) bringing in technologies, conducting training and facilitating transition to alternatives in specific countries, in cooperation with the Regional Centres and individual Parties.

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4.3. Fostering Transparency of Use and Occurrence of POPs and Alternatives. The lack of information on the use and occurrence of POPs is a major challenge for enforcing control measures for POPs, particularly related to the trade of goods and waste.[73] This is caused by a combination of factors such as a lack of legal requirements for public reporting, allowing chemical identities as confidential business information, and a lack of reporting standards and monitoring activities throughout value chains. This issue of a lack of transparency has been discussed extensively.[5,69,72,74] In addition to measuring POPs, the scientific community may investigate how to make information more widely accessible (including industry-generated information that has not been made publicly accessible), and provide guidance and tools to low- and middle-income Parties (e.g., through international standards and databases).[69,75,76]

4.4. Reconciling Existing National Data. A large body of national information and data is made publicly available under the Convention, but are of varied quality and scattered across many places including NIPs, national reporting, registries of exemptions, and GMP monitoring reports and the data warehouse. There is a need for developing tools to extract and compile existing data (e.g., through cheminformatics and natural language processing), reconcile them and other public information, and analyze them to generate policy-relevant knowledge and lessons learned to inform the Convention's implementation.

4.5. Evaluation of the Convention's Effectiveness. The Convention includes an official effectiveness evaluation process (see Section 2.2 above and SI Section S5). Meanwhile, the Convention could benefit from contributions from the scientific community to provide complementary insights.[77] For example, additional monitoring may complement the GMP in terms of the chemical scope (e.g., inclusion of precursors and transformation products to gain insights on total burden),[32,78] media scope (e.g., biota),[79] and geographical scope (e.g., long-term monitoring in cities and indoor environments in addition to remote/background sites to gain insights on effectiveness regarding near-field human exposure and as an "early warning" for sources to remote regions).[80−83] Future studies may also look into data-mining and transforming existing measurements scattered in the literature (including government reports) into searchable open data sets to enhance the evidence base for future official evaluations under the Convention.[28,84−87] Such initiatives may include exploring novel big-data approaches[88] and accounting for variability caused by different sampling, preparation and analytics.[89] Furthermore, current evaluation under the Convention focuses on individual substances; additional studies may investigate the mixture effects of combined exposure to multiple POPs.[90] Also, analysis is needed on the benefits of action and costs of inaction, which could focus on case studies at the national level.

Furthermore, studies may investigate ways to improve current processes under the Convention, including analyzing success factors and lessons learned at the national and international levels. For example, with several recent listings (e.g., decaBDE, SCCPs, and PFOA, its salts and PFOA-related compounds), COP agreed to more exemptions than was recommended by POPRC. In some cases, exemptions go beyond those assessed by POPRC, whereas in some others, POPRC-rejected uses are exempted by COP.[91] Many of those specific exemptions added during the COP negotiations are not exercised by any Parties, or only very small number of Parties register for the exemptions.[50] In addition to timely research on country-specific chemical uses for informing POPRC and COP, studies may investigate the causes of such decisions (e.g., by looking into current information requirements, information collection, and processes for determining the needs for exemptions) and inform ways to minimize the need for further reviews at the COP meetings. Further, studies may look into potential improvements (e.g., new indicators, design of future work) for the effectiveness evaluation framework of the Convention; for reflections from the first official effectiveness evaluation, see SI Section S6.

4.6. Exploring Synergies with Other Environmental and Social Priorities. The sources, environmental fate and behavior, effects and control measures of POPs have strong linkages to other societal and environmental priorities such as human rights, climate change, biodiversity loss, marine plastics, and transition to a circular economy.[57,69,73,92−97] Understanding such linkages can help to strengthen political awareness and commitments to address POPs, and can help to enhance the effectiveness of control measures (e.g., by addressing barriers such as socio-economic pressures and drivers such as right-to-know disclosures).[92,98] Understanding these linkages can also help to identify synergistic solutions that bring cobenefits in multiple priority areas.[95] Hence, further cross- or interdisciplinary studies are warranted to look into the links among POPs and other priority areas (including how control measures of POPs are contributing to the achievement of the 2030 Global Sustainable Development Goals, and vice versa),[95,96] methods and tools to design synergistic solutions,[69,95] and suitable indicators for effectiveness evaluation.[95,96]

5. PRACTICAL GUIDANCE ON PROVIDING MORE EFFECTIVE SCIENTIFIC SUPPORT FOR BOTH CURRENT AND ADDITIONAL NEEDS

Conducting timely research is important, but efforts are required to ensure the visibility and accessibility of such studies to the Convention's implementation. At the same time, attention is needed to balance efforts in scientific research with the application of the precautionary principle (Article 1 of the Convention) so that effective action can be taken without delays caused by scientific uncertainties.

5.1. Pro-Active Communication and Science−Policy Coproduction. Various processes and relevant actors are involved in the Convention's implementation, with diverse conditions and needs. Many of these actors do not necessarily have the capacity for keeping abreast of the (expanding) scientific literature, including having access to the scientific literature behind paywalls. Ideally, a more effective and efficient avenue is to pro-actively foster science−policy coproduction by contacting relevant actors to ask them about their specific needs, discussing possible study design (which can help increase policy salience of the studies), and providing them with research outcomes in an accessible format.

Further, scientists can pro-actively communicate their research results by participating in open calls for information initiated by the Secretariat and participation in the Convention's meetings. Past experience shows that direct participation by scientists at POPRC's meetings, even bringing in unpublished data, can help discussion (e.g., SCCPs).[99,100] In addition, scientists can and should be encouraged to connect with individual Parties (e.g., via national focal points),[101] the

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Secretariat,[102] groups under the GMP, and other key actors in the different policy development stages, as outlined in Section 2 and Figure 1(A) above, and SI Section S1.1. Please see SI Sections S2−S4 as well as rules of procedure of the Convention's meetings,[103] as a good starting point for pro-active communication.

It is important to note that the scientific and policy communities use different languages. Therefore, scientists need to ensure that they communicate with policy actors in a way that is accessible, or to work with knowledge brokers such as the Regional Centres and groups under the GMP. For the former, a wealth of knowledge is available, and learning from the guidance on effective communication under the Intergovernmental Panel on Climate Change (IPCC) is instructive.[104,105]

5.2. Enhanced Data Reporting and Sharing. A major challenge is for independent scientists to find the time and resources needed for pro-active communication with and to support policy actors. Nevertheless, all scientists are strongly encouraged to report their work in an open, transparent and machine-readable manner to fully enable policy actors and other stakeholders to use their work.[106,107] In particular, background details such as method design, implementation, quality assurance, and control, and limitations are as necessary as reporting results. In some areas, such as ecotoxicology,[108] data reporting protocols have been developed through collaboration among academic and regulatory scientists. Such protocols need to be widely adopted and scaled up for other study areas such as environmental monitoring, building on the guidance document under the GMP.[109] In addition, scientific journals can play a key role in systematically enhancing data reporting by introducing such reporting requirements.[110] Further, scientists can take additional steps to make their data accessible through open data platforms such as the GMP data warehouse; such extra efforts should be incentivized, for example, by the funding agencies through independent funding schemes. Concerted efforts by data platforms to develop and widely adopt common information sharing standards are also needed to enable connectivity of information across them.

6. WAYS FORWARD FOR SUSTAINING SCIENTIFIC SUPPORT

In addition to the detailed steps identified above for enhancing scientific support for the Convention's implementation, we strongly recommended the following actions to sustain such efforts.

6.1. Ensuring Sustainable Funding on POPs. Governments, public and private research funding institutions, universities and other scientific institutions need to continuously support research and teaching on the various aspects of POPs.[111] This is crucial not only for the generation of new knowledge for the Convention's implementation, but also for transitioning to open science, strengthening informed policy- and decision-making, and educating future generations of scientists, policymakers, and entrepreneurs capable of addressing the global threat posed by POPs. To do so, new ways of expanding existing funding schemes (e.g., a recently proposed coordinated tax,[112] wide integration into the development aid programs)[113] may be considered, learning from a recent review of economic instruments for financing the sound management of chemicals and waste.[114]

6.2. Establishing a Regular Review of Policy Needs for Scientific Evidence. Although this study outlines, to a certain extent, future policy needs, specific needs may arise in the Convention's future development. Thus, continued monitoring of the needs under the Convention is necessary, as well as making them visible to the scientific community, including extension to also cover country-specific needs. Such efforts may be regularized and coordinated, for example, under a proposed global science−policy body on chemicals and waste,[16] in close cooperation with COP, the Secretariat, POPRC and the Parties.

6.3. Mobilizing the Wider Scientific Community from Different Sectors and Regions. The Convention's implementation requires scientific support from various disciplines, including environmental and analytical chemists, (chem)informaticians, chemical and industrial engineers, epidemiologists, (eco)toxicologists, material scientists, biologists, ecologists, legal experts, economists, occupational safety experts, social scientists, and many others. In addition, not only academic scientists, but also regulatory and industry scientists are key to the picture, as the latter often have detailed information related to production, use and alternatives that is not necessarily available to academic scientists. As we move forward, all these players need to be mobilized, including those who may not be traditionally associated with the Convention's implementation and thus who are not aware of their role that they can play in the implementation. This could be accomplished through collaboration and partnership with national science foundations, national academies, and professional associations. In addition, future work needs to ensure recognition and to reward scientists' time working at the science−policy interface.[16,115]

For decades, the global production and use of chemicals has been experiencing exponential growth with limited scrutiny; this has likely resulted in current humanity operating outside the planetary boundary.[116] Urgent concerted action at the global scale is much needed, including swift societal recognition and reduction of harm caused by chemical pollution. This is particularly critical for POPs and other persistent synthetic chemicals, which can accumulate in the environment and lead to long-term, poorly reversible impacts.[117,118] Here we call on the wide scientific community to greatly step up their research and outreach to enhance scientific support for the Stockholm Convention as an immediate starting point.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c06120.

> Supporting details on the policy development processes under the Stockholm Convention, including on the subsidiary bodies to the Convention, on the *general* policy needs for scientific evidence set out in the Convention's provisions and decisions, on the content included in the previous risk profiles, and on the *specific* policy needs for scientific evidence set out in the Convention's provisions and decisions; conclusions and recommendations from the first effectiveness evaluation of the Stockholm Convention (UNEP/POPS/COP.8/INF/40) and from the *Experience in Using the Effectiveness Evaluation Framework and Recommendations for Future Development* (UNEP/POPS/COP.8/INF/41) (PDF)

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■ AUTHOR INFORMATION

Corresponding Author

Zhanyun Wang − *Institute of Environmental Engineering, ETH Zürich, 8093 Zürich, Switzerland; Empa − Swiss Federal Laboratories for Materials Science and Technology, Technology and Society Laboratory, CH-9014 St. Gallen, Switzerland;* orcid.org/0000-0001-9914-7659; Email: zhanyun.wang@ifu.baug.ethz.ch, zhanyun.wang@empa.ch

Authors

Sam Adu-Kumi − *Chemicals Control and Management Centre, Environmental Protection Agency, Accra GR, Ghana*

Miriam L. Diamond − *Department of Earth Sciences and School of the Environment, University of Toronto, Toronto, Ontario M5S 3B1, Canada;* orcid.org/0000-0001-6296-6431

Ramon Guardans − *WEOG Region Representative for the Global Monitoring Plan of the Stockholm Convention on POPs, Adviser on POPs, Ministry for the Ecological Transition and Demographic Challenge (MITECO), 28046 Madrid, Spain*

Tom Harner − *WEOG Region Representative for the Global Monitoring Plan of the Stockholm Convention on POPs, Air Quality Processes Research Section, Environment and Climate Change Canada, Toronto, Ontario M3H 5T4, Canada;* orcid.org/0000-0001-9026-3645

Agustín Harte − *National Chemicals and Hazardous Waste Directorate, Secretariat of Environmental Control and Monitoring, Ministry of Environment and Sustainable Development, Buenos Aires C1004AAI, Argentina*

Natsuko Kajiwara − *Material Cycles Division, National Institute for Environmental Studies, Tsukuba, Ibaraki 305-8506, Japan;* orcid.org/0000-0003-0201-3721

Jana Klánová − *RECETOX Centre of Masaryk University, the Stockholm Convention Regional Centre for Capacity Building and the Transfer of Technology in Central and Eastern Europe, 611 37 Brno, Czech Republic;* orcid.org/0000-0002-8818-5307

Jianguo Liu − *State Key Joint Laboratory for Environmental Simulation and Pollution Control, College of Environmental Sciences and Engineering, Peking University, Beijing 100871, China;* orcid.org/0000-0002-8878-588X

Estefania Gastaldello Moreira − *Department of Physiological Sciences, State University of Londrina, Londrina 86.057-970, Brazil*

Derek C. G. Muir − *Environment and Climate Change Canada, Canada Centre for Inland Waters, Burlington, Ontario L7S 1A1, Canada;* orcid.org/0000-0001-6631-9776

Noriyuki Suzuki − *Planning Division, National Institute for Environmental Studies, Tsukuba, Ibaraki 305-8506, Japan;* orcid.org/0000-0002-9366-3342

Victorine Pinas − *Institute for Graduate Studies and Research, Anton de Kom University of Suriname, Paramaribo, Suriname*

Timo Seppälä − *Finnish Environment Institute, Contaminants Unit, 00790 Helsinki, Finland*

Roland Weber − *POPs Environmental Consulting, 73527 Schwäbisch, Gmünd, Germany*

Bo Yuan − *Department of Environmental Science, Stockholm University, 106 91 Stockholm, Sweden; Department of Chemistry, Norwegian University of Science and Technology, 7491 Trondheim, Norway;* orcid.org/0000-0002-2043-8128

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.1c06120

Notes

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