Front. Environ. Sci. Eng. 2022, 16(6): 81
https://doi.org/10.1007/s11783-022-1559-y

PERSPECTIVE

Emerging contaminant control: From science to action

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Abstract Since the concept of emerging contaminants (ECs) was first proposed in 2001, the global scientific research of ECs has developed rapidly. In the past decades, great progress has been achieved in the scientific research of ECs in China, including the establishment of EC analysis method system, the evaluation of the pollution status, pollution characteristics and environmental risk of ECs in typical regions of China, and establishment of EC control technology system. Continuous progress in scientific research of ECs promoted China's action on EC control. It is planned that the environmental risk of ECs will be generally controlled by 2035 in China. Priority ECs should be screened for environmental management. Although great efforts have been made, the EC control in China still faces tremendous challenges. It is necessary to bridge the gap between scientific research and decision-making management. Based on the science and technology study, various measures such as engineering, policy management and public participation should be combinedly adopted for EC control.

Keywords Emerging contaminants, Priority pollutants, PPCPs, POPs, Control policy

Since Dr. Richardson of the United States Environmental Protection Agency (USEPA) first proposed the concept of emerging contaminants (ECs) in 2001 (Richardson, 2001), the scientific research of ECs has developed rapidly (Fig. 1). Emerging contaminants refer to chemicals that are not included in routine environmental monitoring, but may enter the environment and cause known or potential negative ecological or health effects. They usually include pharmaceuticals and personal care products (PPCPs) (Daughton and Ternes, 1999; An et al., 2022), endocrine disrupting chemicals (EDCs) (Colborn et al., 1993), persistent organic pollutants (POPs) (An et al., 2021) and microplastics (Wang et al., 2020). With the development of environmental monitoring technology, and the deepening understanding of environmental and health hazards of chemical substances, more ECs will be identified, some of which may be regulated in the future.

In the past decades, the Ministry of Science and Technology (MOST) of China and the National Natural Science Foundation of China (NSFC) have initiated quite a few major EC-related scientific research programs (Table S1). Quite a lot of scientific achievements have been achieved during the research process, including the establishment of EC analysis method system, the evaluation of the pollution status, pollution characteristics and environmental risk of ECs in typical regions of China, and establishment of EC control technology system. These achievements provided scientific basis and technical support for China's implement of Stockholm Convention on POPs and environmental management of ECs. It is worth mentioning that several EC-related innovative research achievements won the National Science and Technology Awards of China (Table S2). For example, a program "Environmental pollution characteristics and physicochemical control principles of halogenated POPs" completed by Tsinghua University won the second prize of the State Natural Science Award in 2017, which clearly identified the halogenated POPs contamination profiles in typical environment, developed the catalytic destruction principles for halogenated POPs removal, elucidated the adsorption behavior and mechanisms of PFCs removal, and greatly supported China's implementation of Stockholm convention.

The continuous progress in scientific research of ECs promoted the China's action on EC control. In November 2020, "the Communist Party of China (CPC) Central Committee's proposals for formulating the 14th Five-Year Plan (2021–2025) for National Economic and Social Development and the Long-Range Objectives Through

Received September 13, 2021; Revised December 27, 2021; accepted December 29, 2021; Available online February 25, 2022

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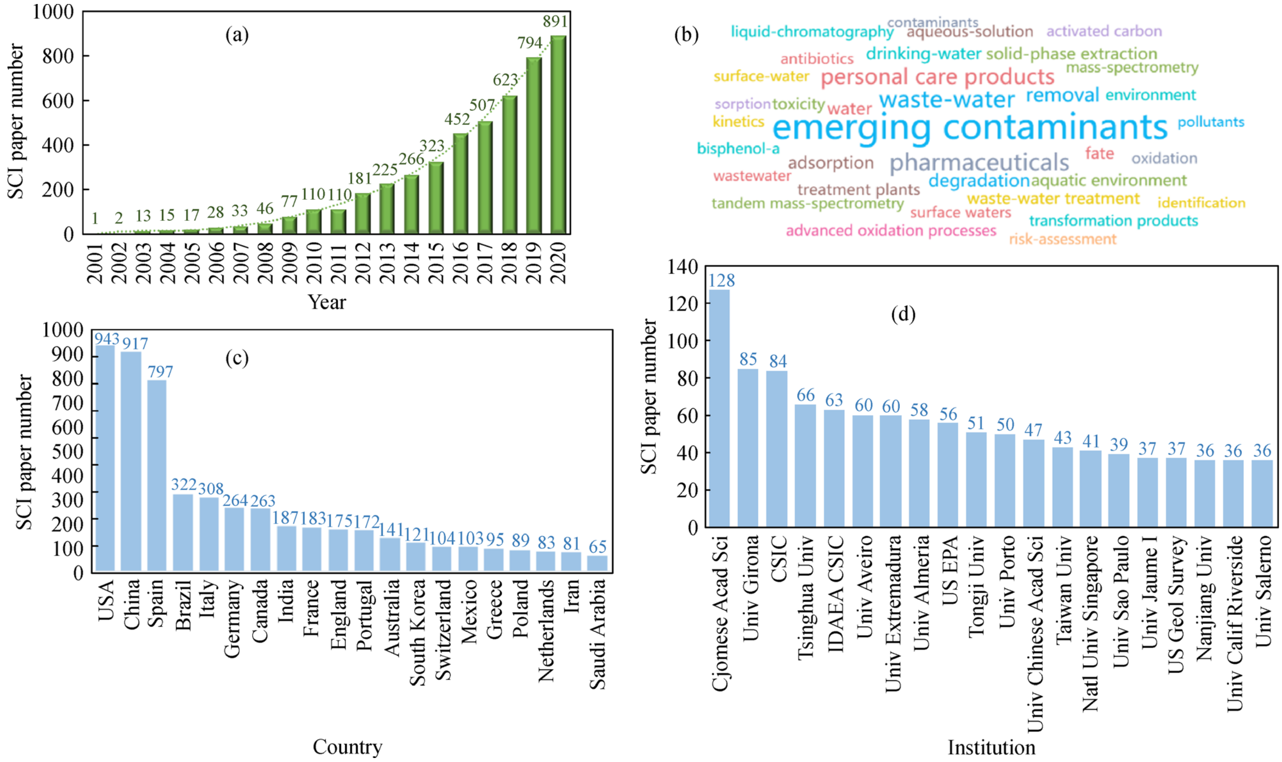

Fig. 1 Publication of SCI papers with the topic of "emerging contaminant" in 2001–2020 in Web of Science core collection. (a) Global SCI publication trend, (b) Keyword cloud analysis, (c) Top 20 countries in related SCI paper publication, China is ranked second, (d) Top 20 research institutions in related SCI paper publication, the Chinese Academy of Sciences (CAS) and Tsinghua University, China are ranked in the top five institutions.

the Year 2035", which was deliberated and adopted by the 5th plenary session of the 19th CPC Central Committee, proposed to pay attention to EC control. In January 2021, the Ministry of Ecology and Environment (MEE), China held a national conference on ecological and environmental protection, which proposed to start to monitor, evaluate and control ECs. In March 2021, the fourth session of the 13th National People's Congress approved "the Outline of the 14th Five-Year Plan (2021–2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035 of the People's Republic of China", emphasizing EC control. In October 2021, the MEE released "the national action plan for the Emerging contaminant control (draft for comments)", which proposes that by 2035, a relatively comprehensive EC control system will be established, the EC environmental risk control capacity will be greatly improved, and the environmental risk of ECs will be generally controlled.

Although China has carried out a large number of researches on ECs and made great progress, the EC control still faces tremendous challenges. For the environmental pollution and risk assessment of ECs, due to the lack of systematic data support, the environmental occurrence and sources of ECs in most regions of China are unclear, the ecological risk level and potential human health risk of a variety of ECs are not well understood. At present, ECs are not covered in routine environmental monitoring. Their environmental monitoring is usually aimed at completing short-term scientific research projects. The time continuity of environmental pollution data of ECs is insufficient, and their change trend over time is unclear. Hence it is impossible to comprehensively evaluate the environmental quality and risk change (Colborn et al., 1993; Wang et al., 2020; Zhu et al., 2020; An et al., 2021, 2022). For the EC control technology, Chinese researchers have conducted a lot of lab-scale researches (Ahmed et al., 2021), and also carried out some pilot and demonstration engineering research, such as per- and polyfluoroalkyl substances (PFASs) disposal technology and PPCPs control technology demonstration. However, due to the lack of EC-related environmental quality or discharge standards, there is a lack of practical application demand of EC treatment technology. Although the revised "Integrated wastewater discharge standard of Shanghai (DB31/199-2018)" includes nonylphenol in the pollutant control items, and the newly revised "Sanitary standard for drinking water (GB 5749) (draft for approval)" includes perfluorooctane sulphonate (PFOS) and perfluorooctanoic acid (PFOA) in the water quality reference indicators, there is still a lack of mandatory national and local environmental standards of ECs. As more and more attention will be paid to EC control, it is expected that more EC-related standards will be promulgated to promote the practical application of EC control technology in the future.

It is impossible to control all the identified ECs. Generally, the control objects are determined by screening of priority pollutants. Since the mid-20th century, some countries have begun to develop the priority pollutants screening framework and list in their environmental management. USEPA first proposed 129 priority pollutants for key control in the late 1970s, and proposed the “Drinking Water Contaminant Candidate List (CCL)” in 1998, which is updated about every five years. ECs such as erythromycin, estradiol, estriol, estrone, 17 α-acetylene estradiol and nonylphenol have been listed on the CCL. In 2001, EU Water Framework Directive (WFD) Decision 2455/2001/EC issued a first list of 33 substances or groups of substances as priority pollutants. In 2013, the revised WFD (Directive 2013/39/EU) stipulated the water environment quality standards for 45 priority pollutants. WFD watch lists of substances for EU-wide monitoring were further proposed in 2015 and 2018. ECs such as estrogen, macrolide, ciprofloxacin and amoxicillin entered the watch list. The former China State EPA passed a blacklist of 68 priority pollutants in water in 1989. The MEE released two batches of priority pollutants list in 2017 and 2019, respectively. However, due to the lack of sufficient environmental exposure and toxicological data, ECs are easily excluded by the prioritization scheme. A research team in Tsinghua University prioritized ECs in surface water in China according to the combined indicators, including potential hazard, potential exposure and risk quotient (Sui et al., 2012; Zhong et al., 2021). However, there is usually a long way from scientific research to sound environmental policy. To bridge the gap between scientific research and decision-making management, it is necessary to carry out ECs environmental monitoring, combine their local pollution characteristics, comprehensively consider the pollution behavior, hazard effects, exposure, ecological and health risks of ECs in specific environment, improve the screening method, and further determine the priority pollutants list based on adequate information exchange among stakeholders. Based on the science and technology study, various measures such as engineering, policy management and public participation should be combinedly adopted for EC control (Fig. 2).

Electronic Supplementary Material Supplementary material is available in the online version of this article at https://doi.org/10.1007/s11783-022-1559-y and is accessible for authorized users.

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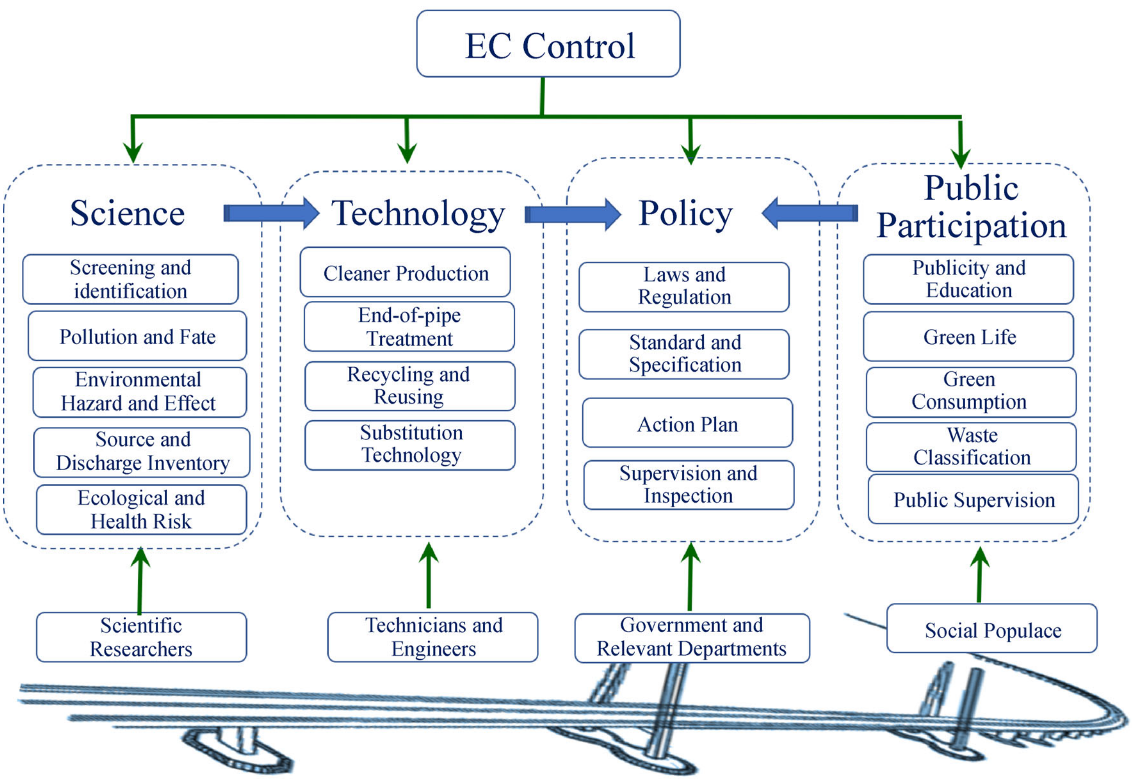

Fig. 2 Build the bridge between science, technology, policy and the public for EC control.

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