

Prioritizing chemicals for environmental management in China based on screening of potential risks

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Abstract The rapid development of China's chemical industry has created increasing pressure to improve the environmental management of chemicals. To bridge the large gap between the use and safe management of chemicals, we performed a comprehensive review of the international methods used to prioritize chemicals for environmental management. By comparing domestic and foreign methods, we confirmed the presence of this gap and identified potential solutions. Based on our literature review, we developed an appropriate screening method that accounts for the unique characteristics of chemical use within China. The proposed method is based on an evaluation using nine indices of the potential hazard posed by a chemical: three environmental hazard indices (persistence, bioaccumulation, and eco-toxicity), four health hazard indices (acute toxicity, carcinogenicity, mutagenicity, and reproductive and developmental toxicity), and two environmental exposure hazard indices (chemical amount and utilization pattern). The results of our screening agree with results of previous efforts from around the world, confirming the validity of the new system. The classification method will help decision-makers to prioritize and identify the chemicals with the highest environmental risk, thereby providing a basis for improving chemical management in China.

Keywords chemicals, screening, risk, environmental management, priority definition

1 Introduction

Socioeconomic development and the progress of science and technology are accompanied by the creation and use of a continuously increasing number of synthetic chemicals and associated chemical species. According to the

Inventory of the Existing Chemical Substances in China (MEP, 2013), more than 45,000 chemical species are currently used in China. Although synthetic and naturally occurring chemicals provide important services to support human production and life, some of these chemicals are associated with serious safety problems in terms of their potential environmental and health risks. These include persistent bioaccumulative and toxic (PBT) chemicals, carcinogens, mutagens, reproductive toxicants, and endocrine disrupters. In China, approximately 3,800 out of 45,000 chemicals have been identified as representing serious safety problems; thus necessitating the development of a strict chemical management program. Identification of the chemicals that pose the largest risks in the context of prioritized chemical management is becoming an imperative field of research. Scholars have implemented a "list type" of management (Swanson et al., 1997), where chemicals are screened based on the specific management purposes and demands for each, and are then added to control lists. Managers can use the resulting lists to prioritize the control and management of those chemicals that pose the greatest safety risks. The development of this type of management method has promoted the establishment of systematic screening of chemicals in many countries.

Since the 1970s, screening methods or technologies have been established for many chemicals and pollutants in developed countries and by international organizations, including the United States (Davis et al., 1994; Swanson et al., 1997; USEPA, 2009, 2012a, b; Singh et al., 2011), the United Kingdom (IEH, 2004), the European Union (Commission EU, 1993; Lerche et al., 2002; ECHA, 2010), Canada (Environment Canada, 1999), and Denmark (DME, 2009). Statistics compiled by organizations in the U.S., Japan, Europe, and other developed countries show that hundreds of chemical screening technologies or systems have been adopted and applied for chemical management. Even a single agency, such as the United States Environmental Protection Agency (USEPA), may

implement multiple types of screening technologies or systems in their practical management of chemicals. These include: 1) in the U.S: the chemical hazard evaluation for management strategy (Davis et al., 1994; Swanson et al., 1997), the priority pollutant ranking system (USEPA, 1984), and the Agency for Toxic Substances and Disease Registry (ATSDR) screening priority management method for harmful substances (USEPA and ATSDR, 2007); 2) in the European Union: a priority-setting method based on the comprehensive monitoring and modeling model of the European Union (Lerche et al., 2002) and the European Risk Ranking (EURAM) method (Commission EU, 1993); and 3) in Australia: the National Environment Protection Council (NEPC) material screening method (NPI Technical Advisory Panel, 1999). Table 1 summarizes the main chemical screening technologies and methods that are currently being widely used.

The American Chemical Hazard Evaluation for Management Strategies (CHEMS) and ATSDR methods and the European Union's Combined Monitoring-Based and Modelling-Based Priority Setting (COMMPS) and EURAM methods are sets of risk-based prioritization methods or technologies based on various theories of chemical toxicity hazards, environmental exposure (i.e., an assessment of the risk of exposure to a given chemical),

and risk assessment. Based on these theories, various methods have been identified to evaluate the potential risks for the eco-environment or for human health. Research on screening technologies and systems has included the following screening methods: qualitative evaluation (e.g., the World Health Organization carcinogen screening; UNDP et al., 2005), quantitative calculations (e.g., the potential hazard index method; USEPA, 1979), and combined qualitative–quantitative methods (e.g., the CHEMS method). Since the late 1990s, the qualitative–quantitative method, also known as the “comprehensive scoring method”, has been the dominant chemical screening method. The methods of CHEMS and ATSDR, the grading screening system for priority pollutants in the U.S., the methods of EURAM and COMMPS in the European Union, and the Australian NEPC methods are all qualitative–quantitative methods, which are regarded as the most widely used and mature approach (Fu et al., 1990; Zhou et al., 1991). As a screening method, this approach has the advantage of being relatively simple to apply to practical management activities.

In contrast with the abovementioned screening technologies and systems, Chinese chemical screening methods have not been officially adopted or implemented. This is because China's management capacity and technical level

Table 1 Main chemical screening technologies or methods

Originators	Screening technologies or methods	Methods
Australia National Occupational Health and Safety Committee	Screening method for harmful chemicals in Australia	Expert evaluation
China National Environmental Monitoring Centre	Screening method for priority water pollutants in China (Fu et al., 1990; Zhou et al., 1991)	Expert evaluation
Chinese Research Academy of Environmental Sciences, Beijing Municipal Environmental Monitoring Center	Screening method for the potentially toxic chemicals control list in China	Fuzzy mathematical method
Danish Environmental Protection Agency	Screening method for List of Undesirable Substances in Denmark	Expert evaluation
Environment Canada and Health Canada	Screening method for the Priority Substances List in Canada	Expert evaluation
European Commission	Screening method for substances of very high concern in the European Union	Expert evaluation
European Commission	Screening method for PBT chemicals in the European Union	Expert evaluation
European Commission	Screening method for endocrine disruptors in the European Union	Comprehensive scoring method
Japan's Ministry of Health and Ministry of International Trade and Industry	Screening method for Persistent Bioaccumulative and Toxic (PBT) chemicals under Japan's Chemical Substances Control Law	Expert evaluation
Korea Ministry of the Environment	Screening method for controlled chemicals of Korea's Toxic Chemicals Control Act	Expert evaluation
Norwegian Ministry of the Environment	Screening method for priority substances in Norway	Expert evaluation
U.S. Department of Health and Human Services	Screening method for National Toxicology Program carcinogens	Expert evaluation
U.S. Environmental Protection Agency (USEPA) Office of Pollution Prevention and Toxics (OPPT)	Screening method for Toxics Release Inventory substances	Comprehensive scoring method
USEPA, OPPT	Classification screening system for priority pollutants in the United States	Comprehensive scoring method

have not yet kept pace with the rapidly growing industrial, agricultural, and domestic use of chemicals, resulting in many difficulties in prioritizing the management of the most dangerous chemicals. In this paper, we consider the development of a framework for chemical risk assessment which could potentially result in a remedy for the current situation in China. To do so, we propose a “risk-score method,” based on the theory of risk assessment, in which researchers or managers assess the risk posed by chemicals based on the available hazard data and environmental exposure information, and transform the evaluation results into numerical values that can be easily understood. These values approximate the potential risks of a chemical.

2 Methods

2.1 Selection indices

In the selection of screening indices, there is always a series of observable attributes that are inherent to each chemical, and each attribute reflects a certain degree of hazard created by the chemical. Thus, any screening technology or system should include as many chemical parameters as possible in its indices to provide a more scientific and comprehensive evaluation of the real situation and to avoid subjective bias. However, the purpose of the screening will determine the type of screening indices that should be selected. For example, in the Australian NEPC system, the choice of indices mostly focuses on environmental exposure indicators because the purpose of the screening is to prioritize the management of

chemical pollutants. In contrast, the European Union’s EURAM method is designed to prioritize the evaluation and management of chemicals. Therefore, their choice of indices focuses on indicators of ecological and human health effects.

Because there are no clear provisions for the optimal number of screening indices that would be appropriate, the selection of an index should be based on the scientific, operational, technical, and management requirements of the screening technology or system. In the selection of indices, Rausand (2011) suggested that three aspects of a chemical should be considered: i) the human health effects that might be caused, ii) possible negative environmental effects, and iii) environmental exposure to the chemical. Figure 1 shows the relationships among nine screening indices in these three categories that are commonly used in the risk-score method of chemical screening and that we adopted in the present study.

2.2 Grading and ratings benchmark

Determination of the grading criteria for the chemical screening indices is a key link in the process. The grading criteria are used to determine if a chemical is hazardous and if so, the magnitude of the potential hazard; therefore directly reflecting the scientific results. A combination of qualitative and quantitative standards is used for different indices.

To adapt the risk-score method to accommodate the status of chemical management in China and integrate the approach with international management standards as much as possible, we decided that each screening index

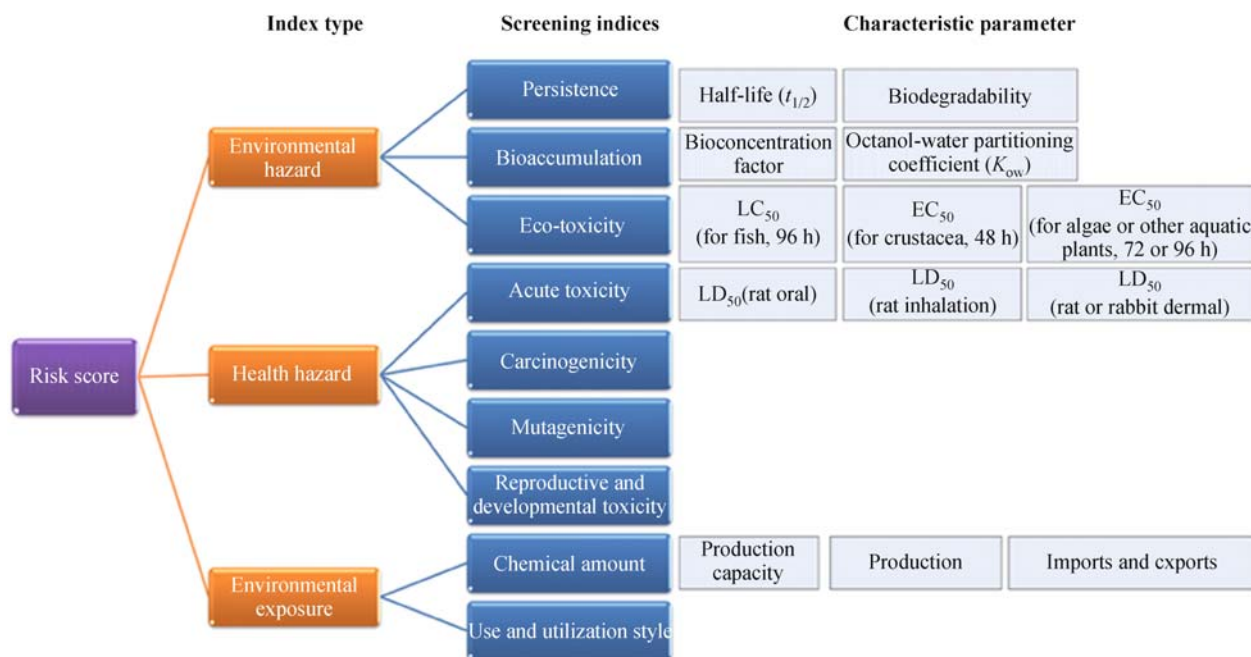


Fig. 1 Indices for environmental management screening priority.

should use the following grading standards:

(i) For indices of persistence and bioaccumulation, we employed the regulations in China's national standard *Persistent, Bioaccumulative and Toxic Substances and High-Durability and Highly Bioaccumulative Substances Decision Method* (GB/T 24789-2009).

(ii) For indices of ecological toxicity, acute toxicity, carcinogenicity, mutagenicity, and reproductive and developmental toxicity, we employed the regulations in the United Nations Globally Harmonized System Grading Standard (UN, 2011).

(iii) For indices of the quantity, usage, and utilization methods, we established grading standards based on a review of the literature and of China's present conditions.

We divided each of the screening indices into four or five levels. For the indices of persistence and bioaccumulation, each index was divided into four grades: I, II, III, and IV, with severity scores of 4, 3, 2, and 1, respectively. For indices of ecological toxicity, acute toxicity, carcinogenicity, mutagenicity, reproductive and developmental toxicity, and usage, we divided each index into five grades: I, II, III, IV, and V, with severity scores of 4, 3, 2, 1, and 0, respectively. For all indices, higher severity scores indicate a higher degree of potential harm. The index representing the chemical amount was also divided into five grades (I, II, III, IV, and V), but assignment of the severity scores

differed from the method used for the other indices. In summary, to make this index conform to the scores for the other indices, we transformed the chemical amount to a value between 0 and 4, with the highest grade (grade I) given a value of 4 and the lowest grade (grade V) given a value of 0. To assign a value to grades II, III, and IV, we calculated the logarithm of each chemical amount, and then used that value as the score for each grade. This both distributed the scores for grades II, III, and IV within the range of 0 to 4 used by the other indices and also allowed us to treat the amounts of different chemicals as a continuous range. The contributions of the index are then refined to reveal the environmental exposure risks in the future. Tables 2 to 10 summarize the criteria we used for each grade with the associated severity score.

2.3 Methods

In this paper, we propose a risk-score method for prioritizing chemical management in China. This method is based on an objective analysis of the potential risks of a chemical and transforms the risk results into a comprehensive evaluation score (*CES*). *CES* is a function of all nine screening indices for a given chemical, multiplied by their corresponding weights. Each index for a screened chemical was scored according to the grading standards in

Table 2 Grading and scoring standards for persistence

Persistence level	Grading standard (half-life)	Severity score
I	> 60 days in water; or > 180 days in sediment or soil	4
II	> 40 days but < 60 days in water; or > 120 days but < 180 days in sediment or soil	3
III	> 16 days but < 40 days in water; or > 90 days but < 120 days in sediment or soil	2
IV	< 16 days in water; or < 90 days in sediment or soil	1

Source: the grading and scoring standards are from China's national standard *Persistent, Bioaccumulative and Toxic Substances and High-Durability and Highly Bioaccumulative Substances Decision Method* (GB/T 24789-2009).

Table 3 Grading and scoring standards for bioaccumulation

Bioaccumulation level	Grading standard	Severity score
(1) Grading and scoring standards for bioconcentration factor (BCF)		
I	BCF > 5000, or other evidence exists based on a high BCF for other species, or monitoring data indicates the potential BCF cannot adequately represent chemicals with high bioaccumulation	4
II	$5000 \geq \text{BCF} > 2000$	3
III	$2000 \geq \text{BCF} \geq 500$	2
IV	BCF < 500, or not applicable	1
(2) Octanol-water partition coefficient		
I	$5 < \log K_{ow} \leq 8$	4
II	$4.5 < \log K_{ow} \leq 5$ or $8 < \log K_{ow} \leq 9$	3
III	$4 \leq \log K_{ow} \leq 4.5$ or $9 < \log K_{ow} \leq 13$	2
IV	$\log K_{ow} < 4$ or $\log K_{ow} > 13$ or not applicable	1

Source: the grading and scoring standards are from China's national standard *Persistent, Bioaccumulative and Toxic Substances and High-Durability and Highly Bioaccumulative Substances Decision Method* (GB/T 24789-2009).

Table 4 Grading and scoring standards for eco-toxicity

Eco-toxicity level	Grading standard	Severity score
I	96 h LC ₅₀ (for fish) ≤ 1 mg/L, and/or 48 h EC ₅₀ (for crustacea) ≤ 1 mg/L, and/or 72 or 96 h ErC ₅₀ (for algae or other aquatic plants) ≤ 1 mg/L	4
II	96 h LC ₅₀ (for fish) > 1 but ≤ 10 mg/L, and/or 48 h EC ₅₀ (for crustacea) > 1 but ≤ 10 mg/L, and/or 72 or 96 h ErC ₅₀ (for algae or other aquatic plants) > 1 but ≤ 10 mg/L	3
III	96 h LC ₅₀ (for fish) > 10 but ≤ 100 mg/L, and/or 48 h EC ₅₀ (for crustacea) > 10 but ≤ 100 mg/L, and/or 72 or 96 h ErC ₅₀ (for algae or other aquatic plants) > 10 but ≤ 100 mg/L	2
IV	96 h LC ₅₀ (for fish) > 100 mg/L, and/or 48 h EC ₅₀ (for crustacea) > 100 mg/L, and/or 72 or 96 h ErC ₅₀ (for algae or other aquatic plants) > 100 mg/L	1

(LC = lethal concentration; EC = effective concentration; ErC = EC based on the reduction in growth rate).

Source: the grading and scoring standards are from the United Nations Globally Harmonized System Grading Standard (4th edition; http://www.unece.org/trans/danger/publi/ghs/ghs_welcome_e.html).

Table 5 Grading and scoring standards for acute toxicity

Acute toxicity level	Exposure route and grading standard					Severity score
	Oral	Dermal	Inhalation			
	/(mg/kg body weight)	/(mg/kg body weight)	Gases/ppmV	Vapor/(mg·L ⁻¹)	Dust and mist/(mg·L ⁻¹)	
I	5	50	100	0.5	0.05	4
II	50	200	500	2.0	0.5	3
III	300	1000	2500	10	1.0	2
IV	2000	2000	5000	20	5	1
V	≥ 2000	≥ 2000	≥ 5000	≥ 20	≥ 5	0

Source: the grading and scoring standards are from the United Nations Globally Harmonized System Grading Standard (4th edition; http://www.unece.org/trans/danger/publi/ghs/ghs_welcome_e.html).

Table 6 Grading and scoring standards for carcinogenicity

Carcinogenicity level	Grading standard	Severity score
I	Known to have carcinogenic potential for humans. Evidence of carcinogenicity in humans is sufficient; or evidence of carcinogenicity in humans is <i>less than sufficient</i> but there is <i>sufficient evidence</i> of carcinogenicity in experimental animals, and strong evidence in exposed humans that the agent acts through a mechanism relevant to carcinogenicity	4
II	Probably carcinogenic to humans. There is <i>limited evidence</i> of carcinogenicity in humans and <i>sufficient evidence</i> of carcinogenicity in experimental animals	3
III	Possibly carcinogenic to humans. There is <i>limited evidence</i> of carcinogenicity in humans and <i>less than sufficient evidence</i> of carcinogenicity in experimental animals	2
IV	Not classifiable as carcinogenic to humans. The evidence of carcinogenicity is inadequate in humans and inadequate or limited in experimental animals	1
V	Probably not carcinogenic to humans	0

Source: the grading and scoring standards are from the United Nations Globally Harmonized System Grading Standard (4th edition; http://www.unece.org/trans/danger/publi/ghs/ghs_welcome_e.html).

Table 7 Grading and scoring standards for mutagenicity

Mutagenicity level	Grading standard	Severity score
I	Known to induce heritable mutations in humans. Positive evidence from human epidemiological studies	4
II	Should be regarded as capable of inducing heritable mutations in the germ cells of humans. Based on convincing study data from experimental animals	3
III	Possibility of inducing heritable mutations in the germ cells of humans. Based on inadequate or limited experimental animal evidence	2
IV	Not classifiable as a potential mutagen for humans	1
V	Probably not a mutagen for humans	0

Source: the grading and scoring standards are from the United Nations Globally Harmonized System Grading Standard (4th edition; http://www.unece.org/trans/danger/publi/ghs/ghs_welcome_e.html).

Table 8 Grading and scoring standards for reproductive and developmental toxicity

Reproductive and developmental toxicity level	Grading standard	Severity score
I	Known human reproductive toxicant. Largely based on the evidence from humans	4
II	Presumed human reproductive toxicant Largely based on the evidence from experimental animals. Data from animals should provide clear evidence of an adverse effect on sexual function and fertility or on development in the absence of other toxic effects	3
III	Suspected human reproductive toxicant. There is some evidence from humans or experimental animals, possibly supplemented by other information, of an adverse effect on sexual function and fertility or on development in the absence of other toxic effects	2
IV	Not classifiable in terms of its reproductive and developmental toxicity to humans	1
V	Probably not a reproductive or developmental toxicant for humans	0

Source: the grading and scoring standards are from the United Nations Globally Harmonized System Grading Standard (4th edition; http://www.unecce.org/trans/danger/publi/ghs/ghs_welcome_e.html).

Table 9 Grading and scoring standards for chemical amount

Chemical amount level	Grading standard (chemical amount, Q ; $t/year$)	Severity score
I	$> 10,000$	4
II	$1,000 < Q \leq 10,000$	$\log Q$
III	$10 < Q \leq 1,000$	
IV	$1 < Q \leq 10$	
V	≤ 1	0

Source: the grading and scoring standards are established by the authors based on a review of the literature and China's present conditions.

Table 10 Grading and scoring standards for use and utilization categories of chemicals

Use and utilization style of chemicals level	Grading standard	Severity score
I	In addition to use as an agricultural chemical, also used as a daily chemical	4
II	In addition to use as an agricultural chemical, also used as an industrial chemical or a research chemical	3
III	Only used as a daily chemical, or not only used as a daily chemical, but also used as an industrial chemical or a research chemical	2
IV	Only used as industrial raw materials in chemical production	1
V	Only used in scientific research and development of chemicals, in small amounts	0

Source: the grading and scoring standards are established by the authors based on a review of the literature and China's present conditions.

Tables 2 to 10 to provide an integrated total score for the chemical. CES has the following general form:

$$CES = f(W_{I1}S_{I1}, W_{I2}S_{I2}, \dots, W_{In}S_{In}), \quad (1)$$

where I_n represents the value of screening index I for chemical n , W_{In} is the weight of screening index I for chemical n , and S_{In} is the severity score for the value of screening index I for chemical n . We identified the weights of the factors by consulting experts (a total of 28 experts in the fields of environment, ecology, medicine, chemical engineering, and health and toxicology) and consolidating their judgments; this approach is commonly used in the development of screening methods.

In this conceptual model, the comprehensive chemical evaluation score is calculated by combining the hazard and

the exposure potential. The resulting score represents the potential risk posed by a chemical. The risk score is calculated by:

$$CES = SE + SH + SX. \quad (2)$$

The three parameters in this equation that are combined to create an integrated CES value equal the sum of the severity scores shown in Tables 2 to 10 for each of the following indices: 1) SE is the score for the environmental hazard, based on three indices (persistence, bioaccumulation, and eco-toxicity); 2) SH is the score for the health hazard, based on four indices (acute toxicity, carcinogenicity, mutagenicity, and reproductive and developmental toxicity); and 3) SX is the score for exposure, based on two indices (chemical quantity and usage).

2.4 Input data and case study

To test the approach, we developed a tiered process for screening the chemicals (Fig. 2). We chose a total of 296 chemicals or chemical categories from domestic and foreign lists according to the following criteria:

(a) chemicals with a large domestic production or import volume (> 100 kt annually) based on Chinese statistics;

(b) chemicals with persistent bioaccumulation, high toxicity, or a potential for endocrine disruption;

(c) chemicals included in the screening lists from five or more countries;

(d) chemicals included in the management list specified by a relevant international environmental convention, and optional substances listed by related conventions;

(e) chemicals that have created a high environmental concern under China's present conditions.

We used the following data source categories to provide values for the nine screening indices listed in Fig. 1 for the 296 chemicals:

(a) Authoritative and comprehensive chemical information databases that have been evaluated by experts or that have been officially approved.

(b) Published science and technology references about the chemicals.

(c) Quantitative structure–activity relationship simulation models. We primarily used this approach when data for a chemical was missing in other resources. The models

we used were the American EPI Suite v4.11 (USEPA, 2012b), PBT Profiler v2.00 (SRC, 2012), and the European Union's Caesar (ECHA, 2009).

3 Results and discussion

We screened the 296 chemicals or chemical categories by applying the risk-score method described in Section 2.3, and calculated a comprehensive evaluation score based on the values of the nine screening indices for each chemical. The higher the severity score, the higher the risk of harm.

The results confirmed that all the selected chemicals have high environmental, health, and environmental exposure potential and therefore have a high comprehensive risk. We listed a total of 28 persistent bioaccumulative and toxic chemicals or chemical species (see Table 11); six of them (lindane, hexachlorobenzene, the perfluorooctane sulfonate class, pentabromodiphenyl ether, kepone [chlordecone], and pentachlorobenzene) are included in the Stockholm Convention on Persistent Organic Pollutants (UNEP, 2012), and the other PBT substances have been managed by developed countries, such as the US and Japan, or by groups of states such as the European Union. The 43 chemicals and chemical species that are highly hazardous to aquatic environments (Table 11) have a high degree of concern, and have therefore been prioritized for international management. Of the 39 chemicals and

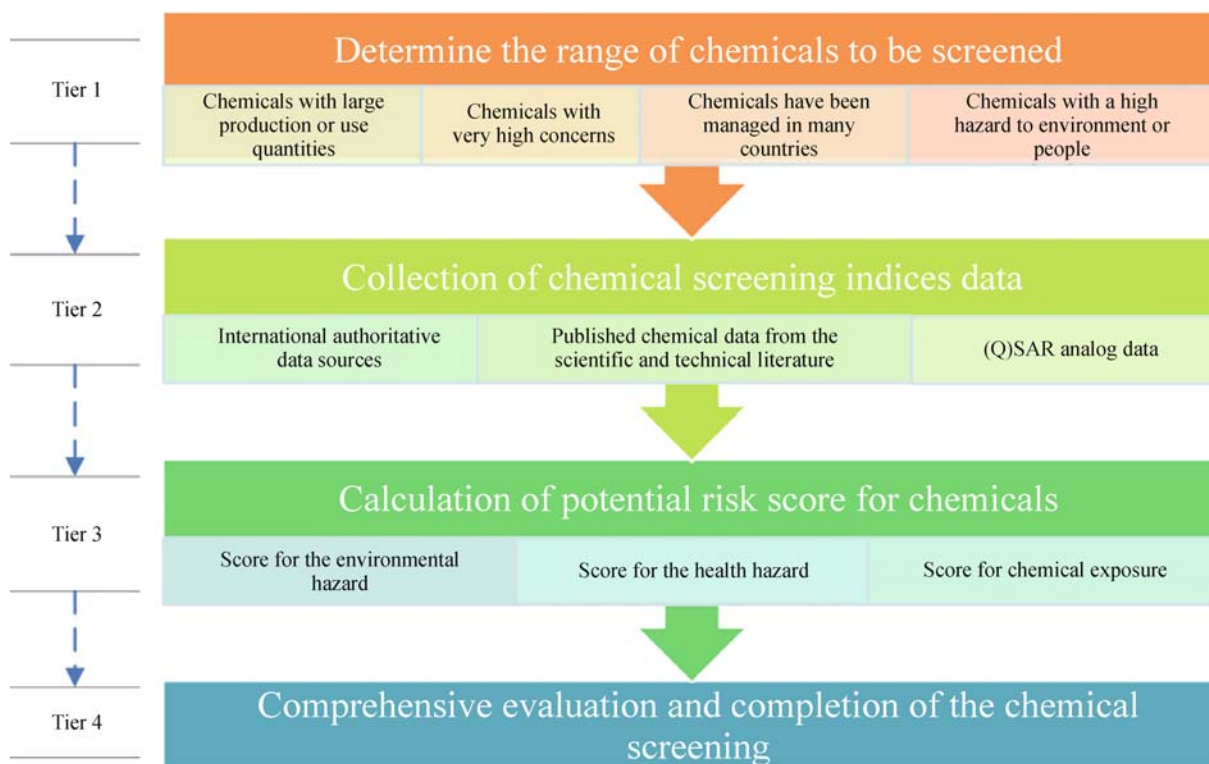


Fig. 2 A tiered process for screening chemicals.

Table 11 Priority environmental management chemicals to be screened by using the risk score method (PBT, persistent bioaccumulative and toxic; POP, persistent organic pollutant)

ID	CAS No.	Chemical	CES	Types of hazard
1	72-43-5	1,1,1-trichloro-2,2-bis(p-methoxyphenyl)-ethane	23	Severely toxic to aquatic organisms, possible human reproductive toxicant
2	87-68-3	1,1,2,3,4,4-hexachloro-1,3-butadiene	19	PBT, severely toxic to aquatic organisms
3	120-82-1	1,2,4-trichlorobenzene	20.65	PBT, severely toxic to aquatic organisms
4	95-50-1	1,2-dichlorobenzene	20.8	Harmful to aquatic organisms
5	106-99-0	1,3-butadiene	20	High persistence, human carcinogen, possible human mutagen
6	542-75-6	1,3-dichloropropene	21.79	High persistence, severely toxic to aquatic organisms
7	106-46-7	1,4-dichlorobenzene	22	High persistence, severely toxic to aquatic organisms
8	3846-71-7	2-(2H-benzotriazol-2-yl)-4,6-bis(1,1-dimethylethyl)-phenol	23	PBT (potential), severely toxic to aquatic organisms
9	1897-45-6	2,4,5,6-tetrachloro-1,3-benzenedicarbonitrile	28	PBT (potential), severely toxic to aquatic organisms, severe toxicity to aquatic organism
10	95-95-4	2,4,5-trichlorophenol	18	High persistence, severely toxic to aquatic organisms
11	732-26-3	2,4,6-tris(1,1-dimethylethyl)-phenol	20	PBT, severely toxic to aquatic organisms
12	120-83-2	2,4-dichlorophenol	18.61	High persistence, toxic to aquatic organisms, endocrine disruptor
13	1836-75-5	2,4-dichlorophenyl 4-nitrophenyl ether	24	PBT, severely toxic to aquatic organisms, endocrine disruptor
14	584-84-9	2,4-diisocyanato-1-methyl-benzene	20	High persistence, severe toxicity to aquatic organisms
15	95-80-7	2,4-toluenediamine	20.18	Toxic to aquatic organisms, possible human carcinogen
16	97-56-3	2-methyl-4-[(2-methylphenyl) azo]-benzenamine	20	Severely toxic to aquatic organisms
17	79-46-9	2-nitropropane	18	Toxic to aquatic organisms, possible human reproductive toxicant
18	101-80-4	4,4'-diaminodiphenyl ether	20.78	Toxic to aquatic organisms, possible human mutagen
19	99-99-0	4-nitrotoluene	18	High persistence, toxic to aquatic organisms, endocrine disruptor
20	100-40-3	4-vinyl-1-cyclohexene	20	Toxic to aquatic organisms, severe toxicity to aquatic organisms
21	81-15-2	5-tert-butyl-2,4,6-trinitro-m-xylene (musk xylene)	20.4	PBT, severely toxic to aquatic organisms, possible human reproductive toxicant
22	79-06-1	Acrylamide	19	Possible human carcinogen, possible human mutagen
23	62-53-3	Aniline	19	Severely toxic to aquatic organisms, possible human reproductive toxicant
24	120-12-7	Anthracene	22	PBT, severely toxic to aquatic organisms
25	7440-38-2	Arsenic and its compounds	26.48	PBT (potential), severely toxic to aquatic organisms, human carcinogen, possible human reproductive toxicant
26	71-43-2	Benzene	24	High persistence, toxic to aquatic organisms, human carcinogen, possible human mutagen, possible human reproductive toxicant
27	50-32-8	Benzo[a]pyrene	22	PBT, severely toxic to aquatic organisms, possible human carcinogen, possible human mutagen, possible human reproductive toxicant, endocrine disruptor
28	85-68-7	Benzyl butyl phthalate	18	Severely toxic to aquatic organisms, possible human reproductive toxicant, endocrine disruptor
29	100-44-7	Benzyl chloride	19	Toxic to aquatic organisms, possible human carcinogen
30	117-81-7	Bis(2-ethylhexyl) phthalate	18	High persistence, possible human reproductive toxicant, endocrine disruptor
31	56-35-9	Bis(tributyltin) oxide	21	PBT, severely toxic to aquatic organisms, endocrine disruptor
32	7440-43-9	Cadmium and its compounds	26.7	PBT, severely toxic to aquatic organisms, severe toxicity to aquatic organisms, human carcinogen, endocrine disruptor
33	75-15-0	Carbon disulfide	18	Toxic to aquatic organisms, possible human mutagen, endocrine disruptor
34	67-66-3	Chloroform	21	High persistence, possible human reproductive toxicant

(Continued)

ID	CAS No.	Chemical	CES	Types of hazard
35	-	Chromate, including: chromic acid, disodium salt (7775-11-3), chromic acid, dipotassium salt (7789-00-6), chromic acid, lead (2+) salt (7758-97-6)	22	Severely toxic to aquatic organisms, possible human carcinogen, possible human mutagen, possible human reproductive toxicant
36	50-18-0	Cyclophosphamide	21	Human carcinogen, possible human mutagen, human reproductive toxicant
37	25376-45-8	Diaminotoluene	18	Toxic to aquatic organisms, possible human carcinogen, possible human reproductive toxicant
38	131-18-0	Diamylphthalate	19	High bioaccumulation, severely toxic to aquatic organisms, endocrine disruptor
39	84-74-2	Dibutyl phthalate	18	Severely toxic to aquatic organisms, possible human reproductive toxicant, endocrine disruptor
40	818-08-6	Dibutyl oxo-stannane	18.85	Toxic to aquatic organisms, severe toxicity to aquatic organisms
41	-	Dichromate, including: dichromic acid, dipotassium salt (7778-50-9), dichromic acid diammonium salt (7789-09-5), and sodium dichromate (10588-01-9)	24	Severely toxic to aquatic organisms, possible human carcinogen, possible human mutagen, possible human reproductive toxicant
42	115-32-2	Dicofol	24	PBT, severely toxic to aquatic organisms, endocrine disruptor
43	25321-14-6	Dinitrotoluene	19	Toxic to aquatic organisms, possible human carcinogen
44	75-21-8	Ethylene oxide	23	Human carcinogen, possible human mutagen, possible human reproductive toxicant
45	1024-57-3	Heptachlor epoxide	21	PBT, severely toxic to aquatic organisms, possible human reproductive toxicant, endocrine disruptor
46	-	Hexabromocyclododecane and all major diastereoisomers that have been identified, including: hexabromocyclododecane (3194-55-6 and 25637-99-4) alpha-hexabromocyclododecane (134237-50-6), beta-hexabromocyclododecane (134237-51-7), gamma-hexabromocyclododecane (134237-52-8)	19.99	PBT, toxic to aquatic organisms
47	118-74-1	Hexachlorobenzene	18	POP, severely toxic to aquatic organisms, endocrine disruptor
48	74-90-8	Hydrogen cyanide	18.54	Severely toxic to aquatic organisms
49	143-50-0	Kepon (chlordecone)	20	POP, severely toxic to aquatic organisms, endocrine disruptor
50	7439-92-1	Lead and its compounds	22	Harmful to aquatic organisms, possible human mutagen, human reproductive toxicant, endocrine disruptor
51	58-89-9	Lindane	22.7	POP, severely toxic to aquatic organisms, endocrine disruptor
52	7439-97-6	Mercury and its compounds	23.97	PBT, severely toxic to aquatic organisms, possible human reproductive toxicant, endocrine disruptor
53	91-20-3	Naphthalene	19	Severely toxic to aquatic organisms
54	7440-02-0	Nickel and its compounds	20	Severely toxic to aquatic organisms, possible human reproductive toxicant
55	98-95-3	Nitrobenzene	21	High persistence, toxic to aquatic organisms, possible human mutagen
56	32536-52-0	Octabromodiphenyl oxide	20.9	PBT, severely toxic to aquatic organisms, possible human reproductive toxicant
57	106-47-8	para-chloroaniline	21.78	Severely toxic to aquatic organisms, possible human reproductive toxicant
58	-	Pentabromodiphenyl ethers	21.48	POP, severely toxic to aquatic organisms
59	608-93-5	Pentachlorobenzene	18	POP, severely toxic to aquatic organisms
60	133-49-3	Pentachloro-benzenethiol,	22	PBT, severely toxic to aquatic organisms
61	82-68-8	Pentachloronitrobenzene	21	PBT, severely toxic to aquatic organisms
62	87-86-5	Pentachlorophenol	27	PBT, severely toxic to aquatic organisms, possible human reproductive toxicant, endocrine disruptor
63	-	Perfluorooctane sulfonic acid, its salts, and perfluorooctane sulfonyl fluoride	18.36	POP, toxic to aquatic organisms

(Continued)

ID	CAS No.	Chemical	CES	Types of hazard
64	79-10-7	Propenoic acid	18	Severely toxic to aquatic organisms, possible human reproductive toxicant
65	129-00-0	Pyrene	19	PBT, severely toxic to aquatic organisms
66	100-42-5	Styrene	19	Toxic to aquatic organisms, possible human reproductive toxicant, endocrine disruptor
67	127-18-4	Tetrachloroethylene	19	Toxic to aquatic organisms, possible human carcinogen, endocrine disruptor
68	78-00-2	Tetraethyl lead	19	PBT (potential), severely toxic to aquatic organisms, possible human reproductive toxicant
69	79-01-6	Trichloroethylene	18	High persistence, possible human carcinogen
70	126-72-7	Tris(2,3-dibromopropyl) phosphate	18	Toxic to aquatic organisms, possible human carcinogen, possible human mutagen
71	75-01-4	Vinyl chloride	20	High persistence, human carcinogen, possible human mutagen, possible human reproductive toxicant

Source: Chemical Registration Center of Ministry of Environmental Protection.

chemical species with a high risk of carcinogenic, mutagenic, or reproductively toxic effects (Table 11), five have been classified as human carcinogens and three as potential human carcinogens by the International Agency for Research on Cancer (IARC, 2012).

The proposed risk-score method is in line with other screening methods used around the world, such as CHEMS in America, EURAM in the European Union, and NEPC in Australia. All of these systems adopted a combination of qualitative and quantitative indicators to screen chemicals. This combination method has become the most widely used and mature chemical screening method. The risk-score method, along with other chemical screening methods, cover some aspects of chemical toxicity and exposure evaluation. However, differences exist between the risk-score method and other screening methods, especially in terms of the indices of environmental exposure. In China, data on chemical emissions and concentrations in various environmental media (e.g., atmosphere, water, soil) were difficult to obtain. Therefore, unlike the CHEMS, EURAM, and NEPC methods, our risk-score method used environmental exposure indices rather than emissions and concentrations to characterize the potential exposure. If reliable emissions and concentration data become available in the future, our method can be modified to account for this additional data.

The international experience, which is codified in the chemical environment conventions and the chemical management strategies currently in use in developed countries, suggests that the chemicals that should be prioritized for environmental management include substances that exhibit persistence, bioaccumulation, carcinogenicity, mutagenicity, reproductive and developmental toxicity, endocrine disruption, or other forms of toxicity. In this paper, we screened these chemicals using a risk-score

method that accounts for the unique aspects of China's use of synthetic chemicals. The evaluation results were favorably in line with international management guidelines.

4 Conclusions

Using an approach based on risk management theory, we consulted a wide range of references and international resources to identify the chemicals that pose the greatest risk to humans and the environment. We then developed a risk-score method to rank these chemicals based on nine indices that accounted for the importance of these chemicals in the Chinese context. The resulting approach largely agreed with previous assessments in terms of the chemicals identified and their relative risks, suggesting that the proposed method provides a scientific and practical method for prioritizing the management of these chemicals in China. However, as is the case for the other screening systems, further investigation should be done to clarify the risk posed by a given chemical or group of chemicals so that our system can be updated to account for the new research results.

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