CHEMICAL ENGINEERING TRANSACTIONS

VOL. 62, 2017

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Fei Song, Haibo Wang, Fang He

ISBN 978-88-95608- 60-0; **ISSN** 2283-9216

DOI: 10.3303/CET1762099

Environmental Impact Prediction and Control of Ecotoxicity Based on System Dynamics

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Eco-toxicant residues permanently stay in the environment and eventually are consumed by plants, animals and humans. Consequently, various diseases and carcinogenic aberrations are caused on humans. Industrial production each year will produce much more eco-toxicants which have been directly discharged into the environment without treatment and ruined the environment in an unpredictable way. The analysis of the mechanism of ecotoxicity unveils the relationship between economic development and the emission load of eco-toxicants. According to the principle of system dynamics, the future emission behavior of eco-toxicants in China was predicted, and the cost required for the eco-toxicant emission control that has surpassed the environment capacity was calculated so as to provide the basis for the development of relevant policy and inputs in the emission control of ecotoxic substances.

1. Introduction

The inorganic toxicant and the refractory organic poison in the environment invade into plants and animals by ways of atmosphere, water, soil. Animal and plant feces and their residues then returned to the environment after the decomposition of microorganisms, thus forming a biocycle of toxic substances. These toxic substances are generally known as ecotoxicants with residues remained in the environment permanently, the chemical pollutants that are highly toxic to biomass and humans, difficult to be degraded. They feature fat-solubility and bioaccumulation, carcinogenicity and teratogenicity and mutagenicity, and endocrine disruption, etc., (Li et al., 2017). These substances mainly include heavy metals and organic chemicals. Such toxicants may cause potentially hazard to terrestrial, aquatic organisms and ecosystems. Currently, their damage to the ecosystem is mainly measured by the concentration of pollutants. China has been developing relevant policies to minimize the impact of ecotoxicants on the environment. However, up to now, there are still relatively few studies made on predicting the emission behavior of ecotoxicants and conducting corresponding governance investments.

2. Mechanism of ecotoxicity

SETAC has proposed the concept of Ecological Toxicity Potential (ETP) (Keyes et al., 2015), the purpose of which is to construct an integrated system that can quantify source and concentration enrichment such that the overall ecological effects of toxicants will be evaluated by ETP emission weights (Lim and Schoenung, 2010). ETP consists of two components: the Environmental Concentration Substance Ratio (CSR) and the environment Impact Concentration Ratio (ICR) of exhaust, ETP can be used to evaluate the exhaust toxicity and better associate the emission with the environmental impact, The specific formula is given as Eq(1) (Haes et al., 2002).

$$ETP_i^{nm} = \frac{\left[CSR_i^{nm} \times ICR_i^{m}\right]}{\left[CSR_x^{nm} \times ICR_x^{m}\right]} \tag{1}$$

Where

Please cite this article as: Jiwei Li, Lixiong Wang, Juanli Guo, Yiqian Zhu, Chang Xu, 2017, Environmental impact prediction and control of ecotoxicity based on system dynamics, Chemical Engineering Transactions, 62, 589-594 DOI:10.3303/CET1762099

$$CSR_i^{nm} = \frac{PEC_i^m}{S_i^n}, \mathrm{ICR}_i^m = \frac{FA*}{C_i^{m*}} \tag{2}$$

Where
ETP_i^{nm}: the ecotoxicological potential of substance i in the environment, based on the stoichiometric amount of this substance to be exhausted into the environment;
CSR_i^{nm}: the environmental concentration ratio of substance i, which indicates the pollutant concentration per unit environment, (mol/m^3);
ICR_i^m: the potential impact of increased concentration of substance i in the environment;
PEC_i^m: the environmental concentration (mol/m^3) predicted for substance i to be continuously exhausted into the environment;
FA*: the impact of standard hazards and the normalized treatment of the potential hazards of different substances;
C_i^{m*}: Benchmark concentration of substance i.
The $ETP_i^{sw,sw}$ and $ETP_i^{sw,soil}$ exhausted into water and soil can be combined when the ETP is calculated as Eq(3).

$$ETP_i^{sw}\left(overall\right) = 0.5 \times ETP_i^{sw,soil} + 0.5ETP_i^{sw,sw} \tag{3}$$

The current impact values for ETP are calculated using the steady-state mass model for continuous emission proposed by Hertwich et al. (2001). Ecotoxic substances mainly include lead, cadmium, arsenic, mercury, copper and other heavy metals as well as some organic chemicals. Anthropogenic discharges will be directly or indirectly exhausted into atmosphere, soil and surface water. The toxic substances in the air pass fall to soil or surface water body through wet and dry sedimentation, and those in the soil flow onto the surface water body through runoff. The toxic substances in the surface water enter the soil by way of irrigation.

3. Relationship between emissions of ecotoxicity substances and economic development

3.1 Emission behavior of ecotoxicity substances in China

Today, the major ecotoxicity pollutants controlled by China are some heavy metals (lead, cadmium, arsenic, mercury, copper, chromium and hexavalent chromium) exhausted into water, as well as volatile phenols and petroleum substances which have different toxicity to and impact on the environment. The toxicities of these substances need to be measured for uniform evaluation on the impact. The pollutant equivalent is an indicator for measuring the ecotoxicity of these substances.
Pollutant equivalent represents synthetic relationship among toxic equivalent, harmful equivalent and cost equivalent of different pollutants or pollutant emissions (Chen et al., 2005), which is used to evaluate the pollution intensity of contaminants. The Administrative Regulations on Levy and Use of Pollutant Discharge Fee issued by the State Council provides the uniform requirements on the pollutant equivalent of different substances. The pollutant equivalent takes the Chemical Oxygen Demand (COD) as the baseline. The "Environmental Quality Standards for Surface Water" GB3838-2002 also specifies the permissible concentrations of contaminants in the surface water. In general, the mercury is most toxic and has a lowest concentration in nature. The toxicological order of these toxicants comes mercury> cadmium> volatile phenol> hexavalent chromium> lead > Arsenic> chromium> petroleum. Based on data from China National Bureau of Statistics, we plot the Table 1.

Table 1: China ecotoxicity substance emission

Sub.	Petroleum (t)	Volatile phenol (t)	Lead (kg)	Mercury (kg)	Cadmium (kg)	Hexavalent Chromium (kg)	Total Chromium (kg)	Arsenic (kg)
2011	21012	2430	155242	2829	35898	106395	293166	146616
2012	17493	1501	99358	1223	27249	70533	190079	128493
2013	18385	1277	76111	916	18435	58291	163117	112230
2014	16203	1378.4	73184	745	17251	34925	132797	109729
2015	15192	988	79429	1079	15819	23597	105288	112101

As seen from Table 1, in recent years, the emission load of ecotoxic substances in China has declined year by year. The hexavalent chromium has dropped from 106395kg to 23597kg, and the emission reduced by 78%, followed by chromium, mercury, volatile phenol, lead, petroleum, arsenic, whose emissions have a least fall, about 23%. Since the emissions do not alone reflect the total toxicity, for example, although mercury is more toxic but its emissions are minimal. The toxic equivalents are further counted as shown in Figure 1.

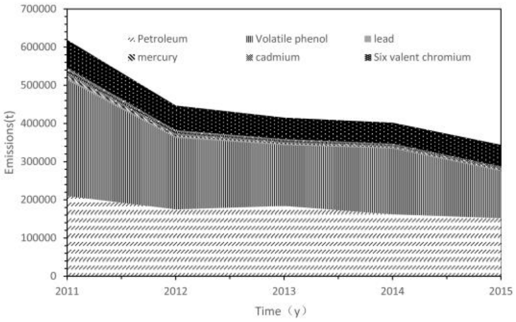


Figure 1: Statistics of toxic equivalents in 2011-2015

It can be found by statistics of toxicity equivalent that the proportion of volatile phenol is always maximum, the next is the petroleum, followed by arsenic, cadmium, mercury, lead, hexavalent chromium, chromium and other substances, which account for nearly equal proportions, falls in between 1179t and 3177t. The toxic equivalent decreases from 618,946t in 2011 to 343,810t in 2015, by 44%.

3.2 Relationship between economic development and ecotoxicity emissions

The absolute value of GDP in current year is used to represent China's economic aggregate. Based on the statistical data of previous years as the data source, the multiple sequences of emissions of GDP, petroleum Oi, volatile phenol OrCH, lead Pb, mercury Hg, cadmium Cd, hexavalent Chromium Cr6 +, arsenic As, total chromium Cr and other ecotoxic substances is taken as bases to analyze the correlation between them.

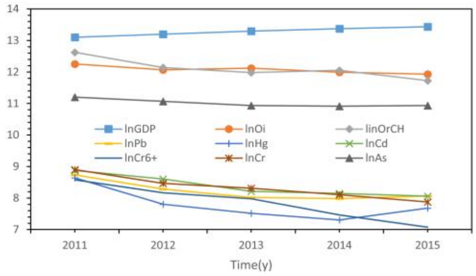


Figure 2: Growing trend of ecotoxicant and GDP

First the natural logarithm is taken for each element to eliminate possible heteroscedasticity and improve the regression precision, made up respectively for lnGDP, lnNOx, as shown in Figure 2. It can be seen from the figure that the emission trends of GDP and ecotoxicity are opposite and can be quantified by correlation coefficient, as Eq(4) (Song et al., 2007).

$$\rho(X,Y)=\frac{Cov(X,Y)}{\sigma X\times\sigma Y} \tag{4}$$

Where: ρ(X,Y) denotes the correlation coefficients of X, Y;
Cov(X,Y) denotes the covariance of both;
σX, σY denote the standard deviation of X,Y, respectively.
Assume X is the natural logarithm of GDP, lnGDP; Y is the natural logarithm of phenolic emissions, lnOi; the natural logarithm of volatile phenol emission, lnOrCH, the natural logarithm of lead emissions, lnPb; the natural logarithm of mercury emissions, lnHg, the natural logarithm of cadmium emissions lnCd, the natural logarithm of hexavalent chromium emissions, Cr6 +, the natural logarithm of arsenic emissions, lnAs, the natural logarithm of total chromium emissions, lnCr, the correlation coefficient between emission of ecotoxic substances and lnGDP can be available. The calculation values are shown in the Table 2.

Table 2: Correlation coefficient between different ecotoxicants and GDP

Oi	CrO H	Pb	Hg	Cd	Cr6+	Cr	As
-0.92	-0.92	-0.88	-0.80	-0.97	-0.98	-0.99	-0.92

As shown in the table 2, there is a negative correlation between the emissions of ecotoxic substances and GDP, Hg has a lowest correlation coefficient, -0.80, with GDP, but still strongly correlated; the chromium is most significantly correlated with GDP, i.e. -0.99, which demonstrates that there is a strong correlation between the emission of ecotoxic substances and GDP development.

4. Dynamics analysis of ecotoxicity emissions and environment impact system

4.1 Construction of ecotoxicity system dynamics model

System Dynamics (SD) is a science developed by Professor Jay W. Forrester of the Massachusetts Institute of Technology to study the dynamic complexity of systems (Liu et al., 2017). Because system dynamics has unparalleled advantages in the study of complex nonlinear systems, it has been widely used in many fields such as society, economy, management, resources and environment (Kalomoiri et al., 2017). At present, the commonly used system dynamics models include Stella, Power -sim, Vensim, etc. The software selected for this study is Vensim PLE.

Currently, the ecotoxic substances in China are mainly dominated by sewage sources. Sewage is discharged into the surface water system by appropriate system, accumulated in surface water, which partially deposits in the sediment, and the other part flows into the ocean via rivers for greater circulation. The toxic substances left in the surface water are partially absorbed by aquatic plants or animals, and the other part is deposited into the soil by way of irrigation, impacting the terrestrial ecosystem. Class I water quality is the best one stipulated in the relevant specification of China. Class III water quality can meet the demands for drinking sources and the growth of animal and plant. The Class I surface water quality is regarded as the background concentration, and the Class III surface water as allowable upper limit to build a dynamic model of ecotoxicity sysetem, with reference to the relationship between the status of China's economic development and the emissions of contaminants, as shown in Figure 3.

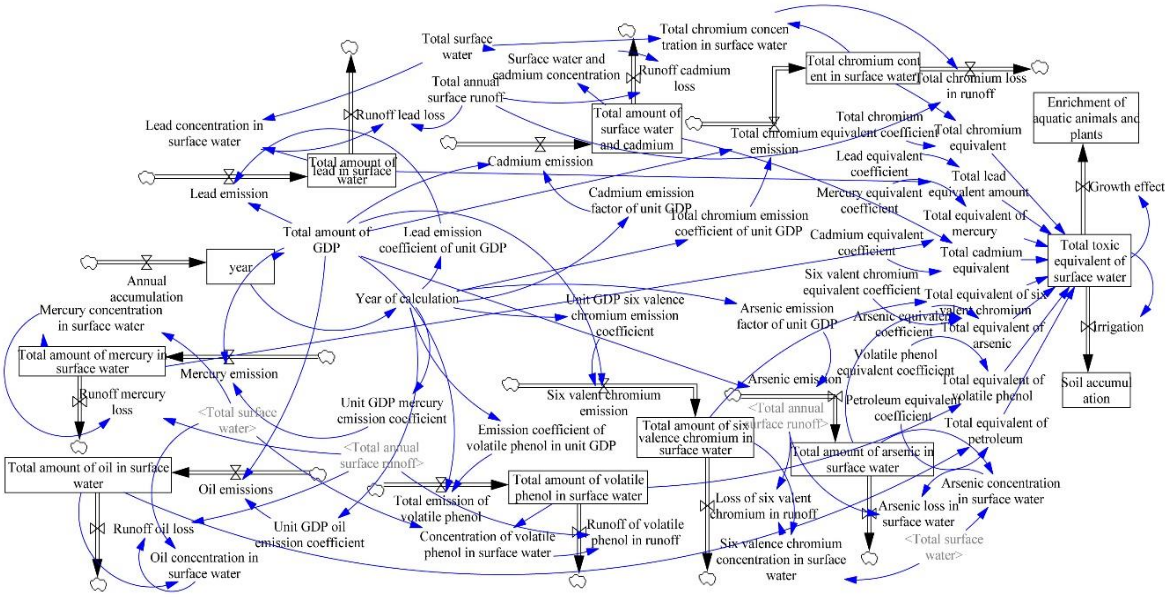
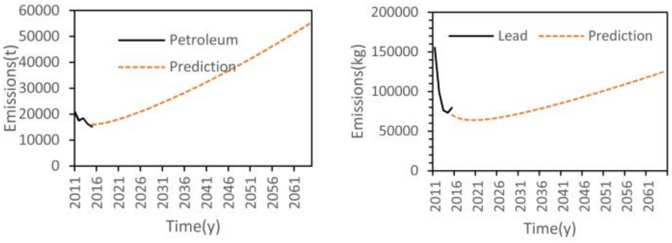


Figure 3: Dynamic model of ecotoxicity system

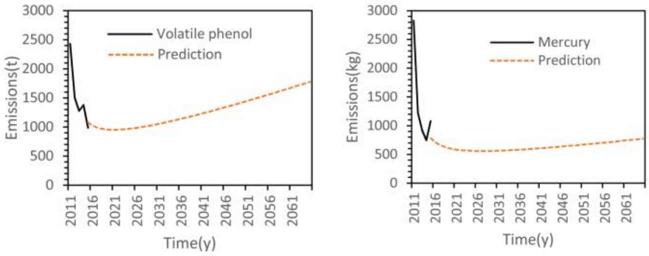
4.2 Projection of ecotoxicological emissions

The model predicts the emissions of different ecotoxicants in the next 50 years, as shown in Figure 4.

As seen from the figure, with the economic development and technological advancement, the emissions of toxic substances basically show the trend of down first and then up. This is mainly due to the technological bottleneck, while the economic growth contributes to slight decrease per unit of substance, however, the gross demands will continue to increase. The gross volatile phenol will hit bottom in year 6 and then continue to rise. It will eventually reach around 1,778 t per annum, while the gross petroleum substances will continue to rise slowly and eventually reach 55,522 t. The growth trend of mercury is relatively gentle and declines from the initial 780kg or so in a year, and then began to rise slowly about 20 years later. The final annual emissions have not yet exceeded the initial value. Other toxic substances basically take on the trend of the first decline and then rise.



(a) Petroleum *(b) Lead*



(c) Volatile phenol *(d) Mercury*

Figure 4: Emissions and projections of ecotoxicants

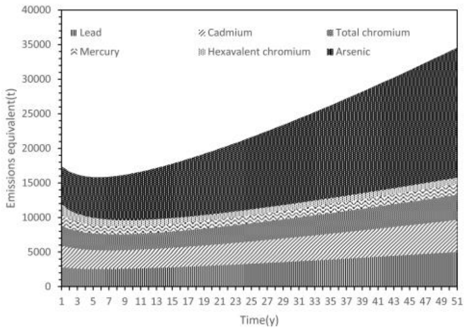


Figure 5: Future prediction of heavy metal emission toxicity equivalent

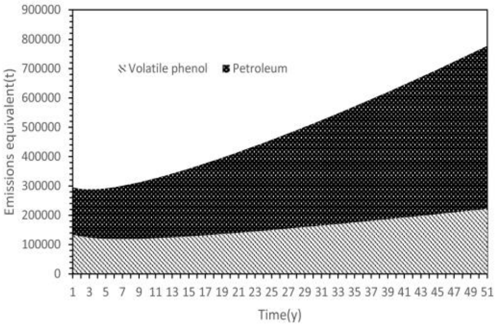


Figure 6: Future prediction of toxic equivalent emissions of ecotoxic substances petroleum and volatile phenol

The emissions of toxic substances never fully reflect its impact on the environment. It is therefore required that the impact of toxicity equivalent shall be predicted, as shown in Figure 5. As we learn, among heavy metal toxicity equivalent, arsenic produces the most impact on the environment, followed by lead and cadmium. In the future environmental protection, we should strengthen to reduce the emissions of the three.

Toxic substances of non-metallic organic matter are mainly volatile phenol and petroleum substances, both of which have the greatest impact on the environmental equivalent, as shown in Figure 6. The petroleum accounts for more than 55% of the organic substances and has to be disposed intensively. In general, the future emissions of ecotoxic substances are on the rise, so that additional emission reductions are required in order to maintain sustainable development.

4.3 Analysis of ecotoxicant governance costs

The model continues to simulate it, as shown in Figure 7, in the next 15 years or so, the ecotoxicity will exceed the allowable value of the environment, and in the next 50 years, the cumulative emissions where the environmental toxic equivalent surpasses the allowable value of environment will reach 26 million t. The environmental treatment cost of ecotoxicant equivalent is 1477$/t. In the future, a total of USD 38,400,000,000 is required for environmental investment, converted into Pb equivalent of 130,000 t at the equivalent treatment cost of 295,384$/t.

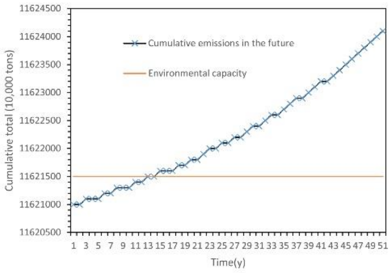


Figure 7: Prediction of gross dose in the ecotoxicity environment in the next 50 years

5. Conclusion

Ecotoxic substances are a class of substances that have a great influence on the environment, and now have caught every country's attention in the world. However, the emissions are subjected to change with different national conditions. Based on scientific calculations and macroeconomic data, the emissions of toxic substances are predicted more accurately in line with the economic development, to develop policies for reasonable emission reduction, only in this way can the emission reduction funds be reasonably arranged in order to achieve more efficient emission reduction targets.

Acknowledgments

This work was supported by National Key R & D Program of China (Grant No. 2016YFC0700201) and supported by National Natural Science Foundation of China (Grant No. 51708394).

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