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Environmental Impact Assessment of Discharged Heavy Metals in Textile Production

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Abstract

Heavy metals discharged from textile production have serious impacts on human beings and the environment. Chemical footprint (ChF) methodology is an important method in quantifying the environmental loads of discharged chemical pollutants. With the help of ChF methodology, this study used the mean impact method to assess the environmental loads of heavy metals discharged from a textile enterprise. The results showed that the ChFs of discharged heavy metals calculated based on the aquatic environment of Lake Tai and Lake Poyang were 1.43E+8L and 4.64E+8L respectively. Zinc was the largest contributor, followed by copper, lead and cadmium for the two lakes.

Key words: *aquatic environment, chemical footprint, environmental impact, heavy metals.*

Introduction

Chemicals play a vital role in modern industrial production [1]. Taking China as an example, over 50000 chemicals are used or produced nowadays [2]. Chemical pollution is increasingly serious with the increasing quantity and types of chemicals. Uncombined heavy metals are discharged into the environment with waste water and waste residue in industrial production [3]. The discharged heavy metals can bio-accumulate through the food chain. They are difficult to degrade and have had serious impacts on human beings and the environment [4, 5]. Assessing these impacts and reducing heavy metal pollution are the common concerns at present [6].

As a footprint tool, the chemical footprint (ChF) was first proposed by Panko and Hitchcock in 2011 [7]. ChF methodology focuses on the environmental impact assessment of chemical use and pollutant emissions. The USEtox model has been widely used in ChF studies, and environmental impacts are now expressed in comparative toxic units (CTU). The definition of ChF based on CTUs reflects the potential environmental impacts of chemical pollutant emissions on species. The results can be converted into volume under certain conditions [8]. Another method for ChF assessment is based on the safe operating space, which is defined as the ratio of the water volume requirement to availability in the study region [9]. This method is more flexible and ChF results are easy to communicate and aid cooperation. Zijp et al. [10] introduced volume-weighted mixture toxic pressure as the quantisation method and calculated the ChF of 630 organic chemicals in Europe and pesticides in the Rhine, Meuse, and Scheldt rivers (RMS). The results showed that the natural carrying capacity of RMS could not tolerate the environmental load of the pesticides.

Currently, researches relating ChF have mainly focused on the environmental impacts of organic chemicals. ChF methodology can also quantify the environmental impacts of heavy metal emissions with toxicity data measured in the experimental environment. However, dissolved organic carbon (DOC) in an aquatic environment is complex with heavy metal ions [11]. The concentrations of OH^- and CO_3^{2-} in a water environment will affect metal speciation, and cations such as H^+, Na^+ and Ca^{2+} in the water environment will compete with heavy metal ions for biotic ligand sites, eventually affecting the toxic effect caused by heavy metals [12]. Therefore, current ChF assessment methods cannot work effectively as to the environmental impacts of heavy metals discharged into different water bodies in different regions. This study aims to calculate the ChF of discharged heavy metals with the AMI method and biotic ligand model (BLM) in order to assess the environmental impacts accurately. This will fill the gap in ChF calculation of heavy metals.

Method and data

The essence of ChF based on dilution theory is to investigate the relationship between the environmental carrying capacity of the study region and the environmental load of production activities [10]. Based on the dilution theory, assessment of the mean impact (AMI) method can quantify the ecological toxicity of chemical pollutants. The ChF obtained by this method represents the available environment volume required to dilute the chemical pollutants to a safe concentration. The impacts of the water environment in the region selected on heavy metal toxicity can be quantified by the biotic ligand model (BLM). The BLM method, which is combined with the theory of gill surface interaction and free ion activity, incorporates the competition of free heavy metal ions with other naturally occurring cations, together with complexation by abiotic ligands for binding with the biotic ligands [13]. The ChFs of heavy metals discharged to the selected water body can be calculated with ***Equation (1)***:

$$ChF = \sum_i^n C_{wi} \cdot V \cdot \frac{\gamma}{HC_{50i}} \cdot \frac{Dis_{ei}}{Dis_{ai}} \quad (1)$$

where, C_{wi} – is the exposure concentration of heavy metal i in the aquatic environment of the study region, mg/l; V – the volume of the aquatic environment in the study region, l; HC_{50i} – the concentration value of heavy metal i corresponding to 50% of the potentially affected fraction (PAF) of species on the curve of species sensitivity distribution (SSD), mg/l; γ – the conversion coefficient of HC_{50} to HC_5, with the value of

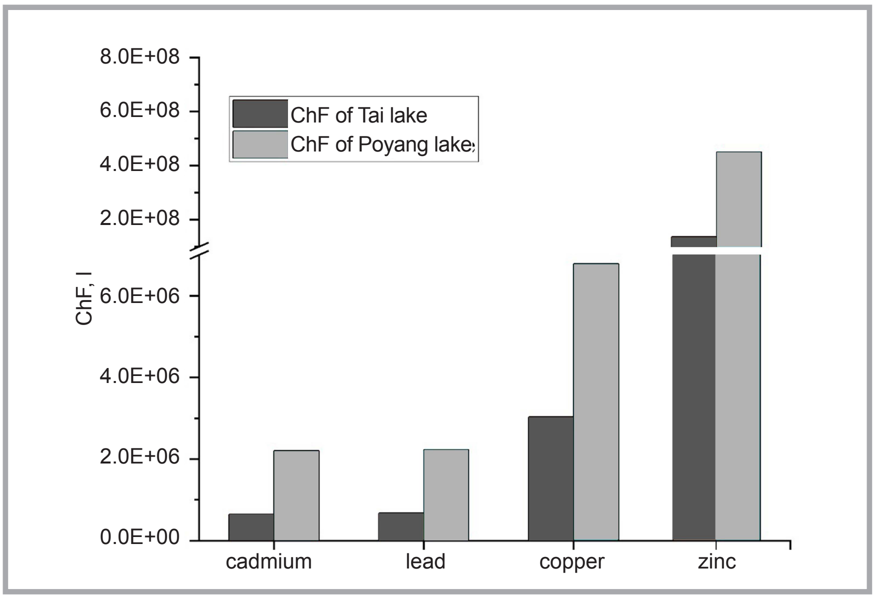

Figure 1. *ChFs of four heavy metals in two lakes.*

146 [14]; Dis_{ei} – the dissolved concentration of heavy metal ion i at 50% mortality in the experimental environment, mg/l; Dis_{ai} – is the dissolved concentration of heavy metal ion i at 50% mortality in the aquatic environment, mg/l.

C_{wi} can be regarded as the steady-state concentration of heavy metal i in the aquatic environment of the selected region after fate. C_{wi} can be calculated as follows, ***(Equation (2))***:

$$C_{wi} = \frac{Q_i \cdot f_{wi}}{V} \quad (2)$$

where, Q_i is the emission quantity of heavy metal i, mg and f_{wi} is the mass fraction of heavy metal i in the aquatic environment of the study region after fate, dimensionless.

The toxic effect of heavy metals is related to the concentration of free heavy metal ions. The fixed lethal accumulation at 50% mortality is the concentration of the associated metal-biotic ligand complex [1]. Due to the water quality differences of different water bodies, the concentrations of free heavy metal ions corresponding to the same concentrations of metal-biotic ligand complexes are different. A coefficient was used to quantify the impacts of the water environment on the toxicity of heavy metals. The ratio of Dis_a and Dis_e indicated the influence coefficient of aquatic environment for toxicity, where the greater the coefficient, the stronger the inhibition of the aquatic environment to heavy metal toxicity. HC_{50} based on the aquatic environment can be calculated as follows, (***Equation (3))***:

$$HC_{50ai} = HC_{50i} \cdot I_{ai} = HC_{50i} \cdot \frac{Dis_{ai}}{Dis_{ei}} \quad (3)$$

where, HC_{50ai} is the HC_{50} of heavy metal i in the aquatic environment, mg/l and I_{ai} is the influence coefficient of the aquatic environment for the toxicity of heavy metal i, dimensionless.

In this study, the ecological threshold was defined as the safe concentration to protect most of the aquatic organisms (95%) from the direct impact of discharged heavy metals, which can be calculated as follows:

$$HC_{5ai} = \frac{HC_{50ai}}{\gamma} \quad (4)$$

where, HC_{5ai} is the ecological threshold based on the aquatic environment, mg/l.

According to the equations above, the ChF calculation method for discharged heavy metals based on the aquatic environment of selected regions can be converted into the following form:

$$ChF = \sum_i^n \frac{C_{wi} \cdot V}{HC_{5ai}} \quad (5)$$

In this study, we calculated the ChFs of four kinds of heavy metals discharged by a textile dyeing enterprise in 2019. The data of discharged heavy metals were collected from the Institute of Public & Environmental Affairs database. Two lakes were selected as the simulative regions to illustrate the different impacts. Aquatic environment data of the two lakes were collected from former research references [16-21]. Toxicity experimental data of heavy metals were obtained from the USEtox model.

Results and discussion

Figure 1 shows the ChFs of four heavy metals (i.e., cadmium, lead, copper and zinc) based on different regions. The total ChF based on the aquatic environment of Lake Tai (ChF_{Tai} for short) was 1.43E+8L. Zinc contributed the most to the environmental load with a result of 1.39E+8L. The ChFs of copper, lead and cadmium were 3.03E+6L, 6.75E+5L and 6.45E+5L, respectively. The total ChF based on the aquatic environment of Lake Poyang (ChF_{Poyang} for short) was 4.64E+8L. Zinc was also the largest contributor, followed by copper, lead and cadmium. ChFs calculated based on the aquatic environment of Lake Poyang for cadmium, lead, copper and zinc were larger than those calculated based on the aquatic environment of Lake Tai.

The aquatic environment of Lake Tai, with low pH as well as relatively high concentrations of DOC and ions (inorganic anions and major cations), had a great influence on the ecotoxicity of heavy metals. DOC can ameliorate the ecotoxicity of heavy metals by its ability to bind heavy metals [22]. High concentration of DOC means that the metal-DOC complex has a higher proportion in the speciation of heavy metals, and that the concentrations of heavy metal ions that can bind to biotic ligand sites are lower, thereby reducing bioavailability to target surfaces such as gills [22]. Ions in water affect the toxicity of heavy metals by their effects on both the organism and metal speciation. Inorganic anions decrease the availability of heavy metals by complexing with them. Mg^{2+} and Ca^{2+} (particularly the latter) not only play a significant role in decreasing heavy metal action at transport sites by apparent competition but also in decreasing ionic losses associated with toxicant action by stabilising the paracellular junctions in the gill epithelium [23, 24]. H^+ showing a low pH not only changed the speciation of heavy metals but also offered protection by competing with them for binding sites [25].

Changes in heavy metal toxicity based on the aquatic environment of Lake Poyang are shown in ***Figure 2***. The abscissas

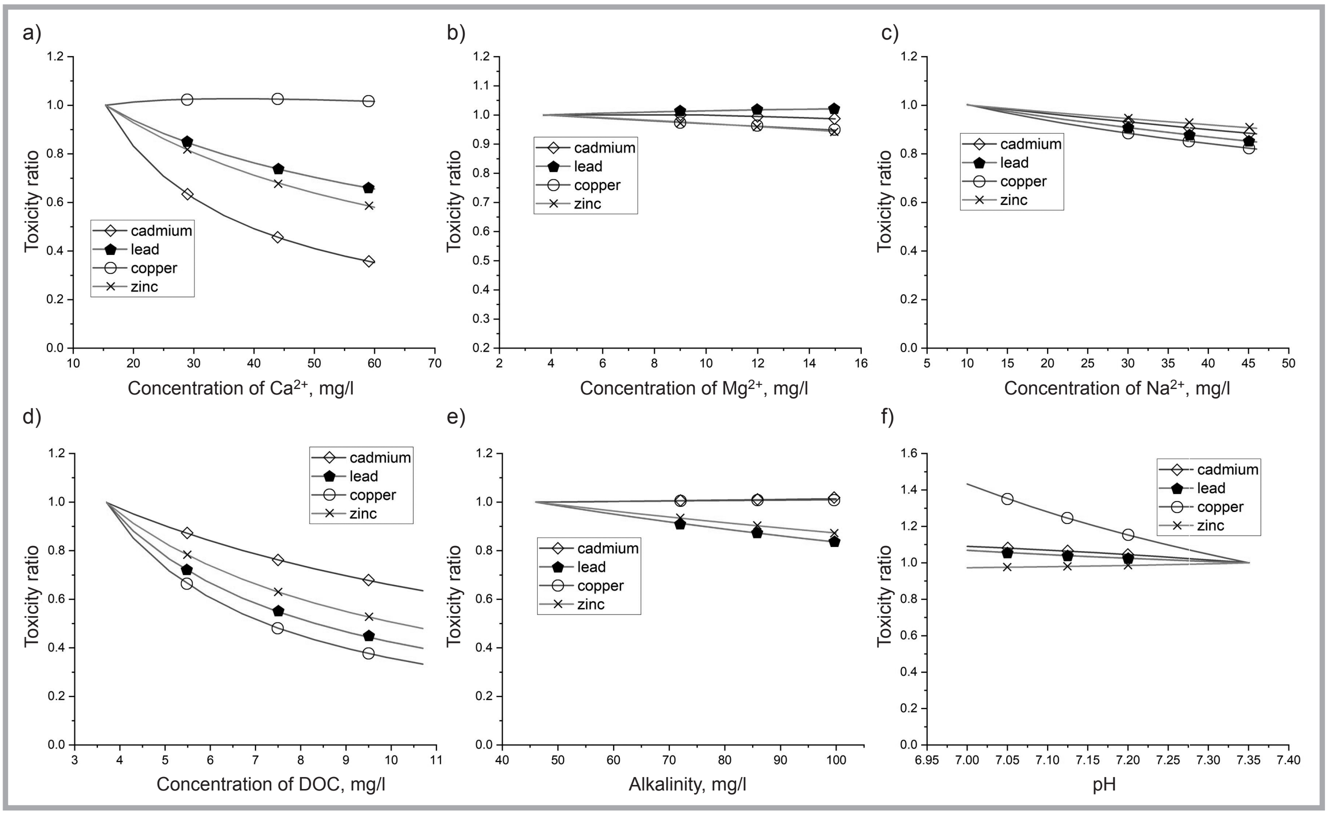

Figure 2. *The influence of different water quality parameters on the toxicity of heavy metals.*

represent the water quality parameters and the ordinates the ratio of heavy metal toxicity in the aquatic environment with a corresponding concentration to that in the aquatic environment of Lake Poyang. The intersection of lines in each graph is the datum of each variable.

As can be seen from ***Figure 2***, the concentrations of Ca^{2+} and DOC had an obvious effect on the toxicity of cadmium. In the BLM model, Ca^{2+} played a protective role, where it was the major cation that competed with the free Cd^{2+} for the binding sites. The strength of DOC-Cd^{2+} binding was about 10 times greater than that of gill-Cd^{2+} binding; therefore, DOC can effectively reduce the toxicity of cadmium [13]. This is the main reason for the largest reduction ratio of ChF caused by cadmium. The effect of DOC concentration on the toxicity of copper was entirely more obvious, while Ca^{2+} and alkalinity had little effect on the toxicity of copper. The inhibitory effect of Na^{+} and Mg^{2+} on copper toxicity was less than that of DOC. Therefore, the influence of Na^{+} and Mg^{2+} on copper toxicity was inapparent in the limited concentration range [26]. On the other hand, the decrease in pH had an obvious effect on the toxicity of copper. Although more H^{+} will offer protection by competing with Cu^{2+}, reducing pH will change the speciation of copper and increase the concentration of Cu^{2+}, having stronger complexation ability with biological ligands, which was the reason that the reduction ratio of the ChF caused by copper was the smallest.

Conclusions

Heavy metals discharged from industrial production have serious impacts on the environment as well as human beings. As a footprint indicator, ChF quantifies environmental loads by evaluating the performances of discharged pollutants. However, current ChF methodology has the main weakness of low distinguishing ability for quantifying the environmental loads of heavy metal based on different regional aquatic environments.

In this paper, we improved ChF methodology by using the BLM model and considering the impact of the aquatic environment on environmental loads. ChFs of four kinds of heavy metals were calculated based on the aquatic environment of two regions. The results showed that ChF_{Tai} was smaller than ChF_{Poyang}. Zinc was the largest contributor for the total ChFs of the two lakes, followed by copper, lead and cadmium.

Currently, the lack of availability of pollutant data on auxiliary composition and emission is one of the limiting factors for ChF research, which makes it difficult for inventory accounting to reflect real environmental loads. On the one hand, producers are concerned about the effects of auxiliary, and due to the pressure of environmental protection policies, they often pay close attention to the emissions required by the policies. Obtaining relatively real data and building transparent and flexible databases are necessary for ChF research in the future.

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