

Environmental Impact of Anthropogenic Mercury Release in China

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There is increasing public concern regarding the potential risks posed by mercury and mercury compounds. Knowledge of the mercury emission and release inventory, and determination of the main factors that ameliorate the environmental impact of anthropogenic activities, will contribute to environmentally sound mercury management. This study used a life cycle impact assessment to identify the major factors contributing to the overall environmental burden imposed by elemental mercury releases. The environmental impact of the business-as-usual scenario (total impacts = 5.13 GPt) was greater than that of the accelerated technology transformation (ACR) scenario (total impacts = 4.51 GPt), especially in terms of the impact on human health (HH). ACR mainly reduces mercury emissions to air, which affects HH. Compared to its effects on HH, mercury release to the environment has less impact on ecosystem diversity (ED). Mercury release to land had the largest impact on ED, followed by mercury emissions to air and discharge to water. ACR can reduce the harm to HH and marine ecosystems by 12 %. This study provides quantitative information on the environmental impact of mercury release, facilitating strategic management of mercury emissions in line with the Minamata Convention on Mercury (implemented in China in 2017).

1. Introduction

China is the largest emitter of mercury from anthropogenic sources (Zhang et al., 2015). Atmospheric mercury emissions have increased continuously, from 356 t in 2000 to 538 t in 2010, with an average annual increase of 4.2 % (Zhang et al., 2015). In total, 1,501 t of mercury from anthropogenic sources was released to air, water, and land environments in 2016 (Habuer et al., 2021). Anthropogenic activities have aroused great concern in terms of the negative impact of mercury on the natural environment and human health (Habuer et al., 2018). In China, rapid industrial development and a lack of waste treatment facilities has resulted in large amounts of mercury being transported to aquatic systems via sludge, fertilizers, lime, manure, and atmospheric deposition (Tong et al., 2013). Public concern over the potential risks posed by mercury and its compounds has been increasing. Knowledge of the mercury emission and release inventory, and the main factors that ameliorate the environmental impact of anthropogenic activities, will contribute to environmentally sound mercury management, which is becoming increasingly urgent in China since implementation of the Minamata Convention on Mercury (MCM) in 2017.

Extensive research has examined issues associated with the toxicity of mercury and mercury compounds worldwide (Li et al., 2020), including their negative impacts on ecosystems (Liu et al., 2018) and human health (Rodrigues et al., 2019). Inventories of air (Habuer et al., 2019), water (Tong et al., 2013), and land (Ying et al., 2017) emission and releases, particularly atmospheric emissions, have received much attention globally. The inventories to natural environment in China in 2016 (Habuer et al., 2021a), and a time-series inventories in 2016-2019 (before and after MCM) have been conducted (Habuer et al., 2021b). The environmental performance of mercury-containing goods, such as fluorescent lamps (Tan et al., 2015) and thermometers (Gavilan-Garcia et al., 2015), as well as the impact of mercury-containing waste (Busto et al., 2015), and recycled industrial mercury-containing waste (Qi et al., 2017), have been studied using a life cycle assessment (LCA) approach. A lack of surveys about using LCA to evaluate the environmental impact of total mercury releases resulted in anthropogenic sources has been observed. The objective of this study was to obtain

quantitative data on the environmental impact of total mercury releases, to facilitate strategic management thereof as the MCM is implemented in China. To address this issue and provide scientific information for policymakers, this study adopted the LCA approach. Inventories for two scenarios were devised to understand pollution release. Then, a life cycle impact assessment (LCIA) was used to identify the major factors contributing to the overall environmental burden. The environmental impact of anthropogenic mercury release in 2019 was compared between the scenarios.

2. Materials and methods

2.1 System boundary

Figure 1 shows the system boundary for the LCA of anthropogenic mercury release in China. There are 5 main anthropogenic mercury sources, namely extraction and combustion (C1), mineral production (C2), intentional uses (C3), secondary metal production (C4), and waste treatment (C5) (Habuer et al., 2021a), and 66 “sub-sources”. A distribution model considering both the initial distribution (i) and redistribution (r) was used to evaluate the overall distribution. An output scenario (OS) distributed mercury among various sinks and intermediate reservoirs, including air, water, land, stocks, and stabilization holdings. The term “stock” implies mercury is stored in product/by-products/wastes due to a delay of 1 year (y) or more in disposal or treatment. The term “stabilization” implies that mercury is properly treated and stably stored. Total mercury release to the environment was the system boundary for the impact assessment. The total elemental mercury input in tons (t) from the five main anthropogenic mercury sources in 1 y (2019) was the functional unit. Life cycle inventory (LCI) data were obtained from a previous study (Habuer et al., 2021b). The detailed calculation method for the inventories is reported elsewhere (Habuer et al., 2021a).

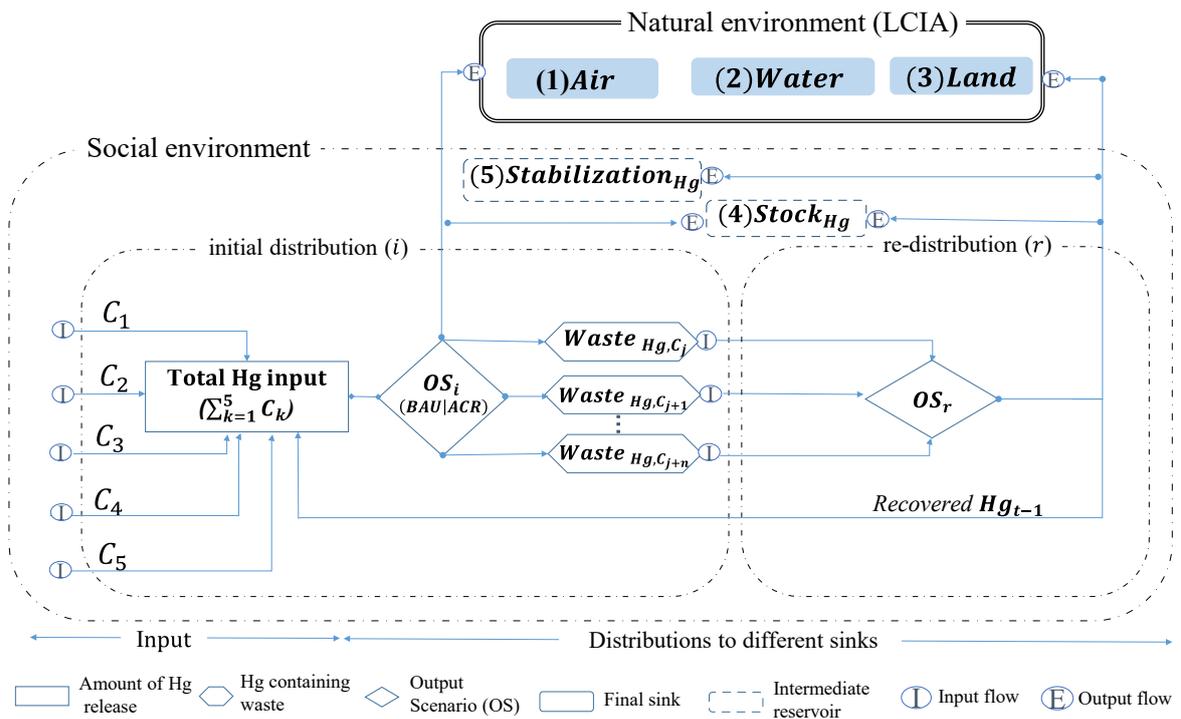


Figure 1: System boundary for environmental assessment of anthropogenic mercury release in China

2.2 LCIA methodology

LCIA is a systematic, widely used method for evaluating the environmental burden of a product (Khongprom et al., 2020), process, or activity over its life cycle by analysing the materials and energy used, and the emissions generated (Qi et al., 2017). The LCIA results in this study, i.e., normalized global values, were obtained using the ReCiPe Endpoint (H) and World ReCiPe H/A functions, and an average weighting set. The most authoritative impact assessment method was selected for the LCIA here. The ReCiPe 2016 (Huijbregts et al., 2017) converts many LCI results into a few indicator scores that represent the severity of the environmental impact; 18 midpoint impact categories and 3 endpoint damage categories can be obtained. This work related to only four impact

categories [human toxicity (HT), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), and marine ecotoxicity (MET)] and two damage categories [damage to human health (HH) and damage to the ecosystem diversity (ED)] (Table 1). The effects of the resources used, i.e., water, electricity, chemical compounds, diesel, concrete, and land, are outside the system boundary because it is impossible to capture the inventories for the treatment processes of all 66 subcategories.

Table 1: Impact and damage categories related to this study

Area of protection	Impact categories	Damage categories	Units
Human health	Human toxicity (HT)	Damage to human health (HH)	Disability-adjusted loss of life years (DALY, years) ¹⁾
Natural environment	Terrestrial ecotoxicity (TET) Freshwater ecotoxicity (FET) Marine ecotoxicity (MET)	Damage to ecosystem diversity (ED)	Time-integrated species loss (species, years) ²⁾

¹⁾ life years lost in the human population; ²⁾ number of species lost over time.

After the MCM came into force, two “technology transformation scenarios” were defined (Habuer et al., 2021b). In the business-as-usual (BAU) scenario, it is assumed that all existing technologies were retained. In the accelerated technology transformation (ACR) scenario, accelerated innovation and use of the best available technologies (BATs) are assumed. Note that the mercury mining and consumer goods sectors responded to the MCM in 2019. Several technology transformations occur under the ACR scenario. Specifically, the subcategories of gold extraction with mercury amalgamation, chlor-alkali production, coal-fired power plants, oil combustion, natural gas extraction and refining, and waste incineration are assumed to have undergone technological transformations, in terms of treatment processes, after the MCM came into force. For example, in the natural gas extraction sector, refining relied on a gas-processing technology without mercury removal before the MCM but switched to a process involving mercury removal thereafter; details are given in Habuer et al. (2021b).

3. Results and discussion

3.1 Life cycle inventory

The total mercury input in 2019 was 2,152 t, of which 884 t were released to the natural environment under the BAU scenario (Figure 2(a)). In the initial distribution, around 373, 119, and 21 t of mercury were emitted to air, water, and land. In the redistribution, the amounts were 95, 17, and 260 t. In social environments, 345 t of mercury was stabilized by either appropriate treatment or stable storage, with 872 t being stored in products/by-products/waste due to a delay of 1 y or more in disposal or treatment. Example mercury stocks include the mercury stored in consumer products (batteries, thermometers, etc.) and that stored in the waste acid and smelting slag produced in nonferrous metal smelters.

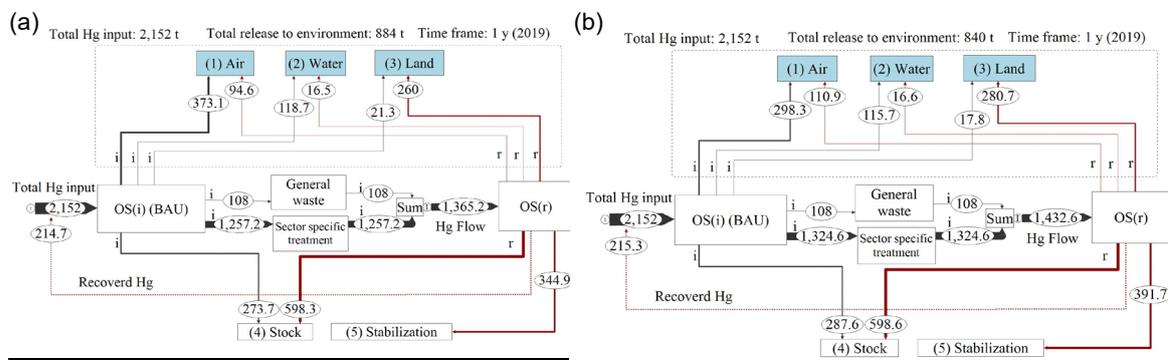


Figure 2: LCI under (a) BAU, and (b) ACR scenarios

The total release to the natural environment was 840 t under the ACR scenario, which was 44 t lower than that under BAU. In the initial distribution, around 298, 116, and 18 t of mercury were released to the air, water, and land. In the redistribution, the respective amounts were 111, 17, and 281 t. In social environments, 392 t of mercury was stabilized and 886 t was stored in products/by-products/waste. In both scenarios, the release to land on redistribution was 12–15 times higher than in the initial distribution, implying that waste treatment/disposal processes, including of general and sector-specific waste, are the largest contributors to mercury release to land. The mercury emissions to the air obviously decreased under ACR in the initial distribution but increased in the redistribution stage. This implies that the best currently available technologies mitigate atmospheric emissions in the initial rather than redistribution stage.

3.2 Environmental burden shown as impact categories

This study analysed the effects of elemental mercury releases on the environment, as reflected in impact categories, using ReCiPe (H) v1.1. Figure 3 shows the environmental burden based on impact categories under the two scenarios. The BAU scenario imposed a greater environmental burden than the ACR scenario (Figure 3). Specifically, the impact on HT and MET was around 12 % lower in the ACR than BAU scenario. This implies that applying ACR can reduce harm to human health and marine ecosystems. The DALY values for HT were 1.75×10^5 and 1.53×10^5 for ACR and BAU; for TET, the values were 18.6 and 18.8 species/y, compared to 0.013 and 0.013 species/y for FET, and 0.046 and 0.052 species/y for MET.

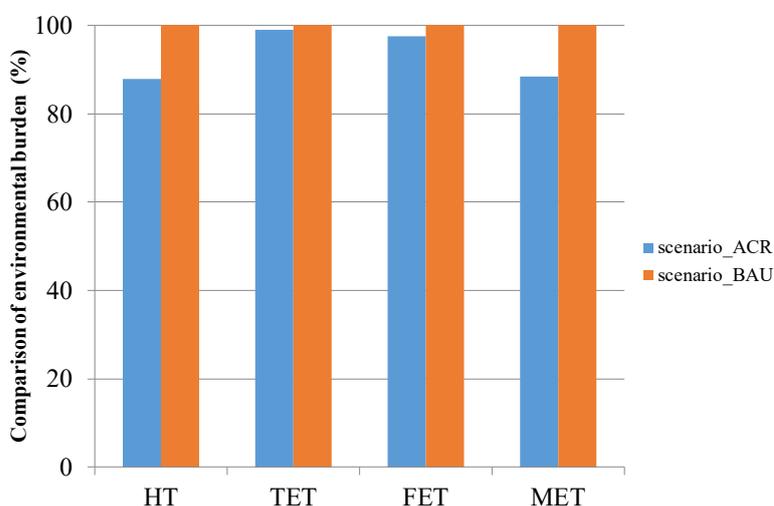


Figure 3: Comparison of environmental burden under two scenarios based on impact categories

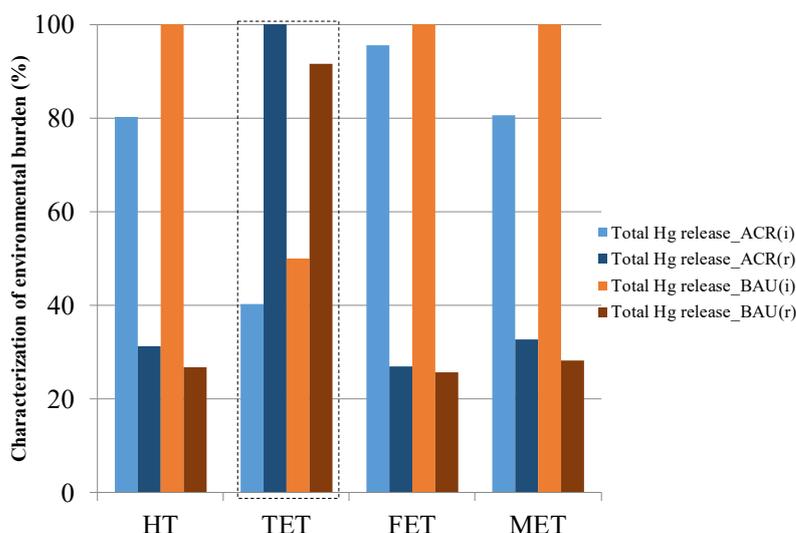


Figure 4: Characterization of environmental burden based on impact categories

The harm to terrestrial and freshwater ecosystems showed little difference between the two scenarios. The harm to human toxicity and marine ecosystems showed relative large difference between the two scenarios as shown in Figure 3. Harm to human health, and to freshwater and marine ecosystems, was higher in the initial than redistribution stage under both scenarios, while the opposite was true for terrestrial ecosystems as shown in Figure 4. This implies that mercury containing waste treatment/disposal (including of general and sector-specific waste) has greater potential for the harm to terrestrial ecosystems, mainly attributed to mercury releases to the land.

3.3 Environmental burden reflected in damage categories

The environmental burden, as reflected in endpoint damage categories, manifested as harm to HH and ED based on normalization of the eco point (Pt) as shown in Figure 5. The environmental impact of the BAU scenario (total impacts = 5.13 GPt, where 1 GPt = 1×10^9 Pt) was higher than that of the ACR scenario (total impacts = 4.51 GPt), especially the impact on HH. The ACR scenario reduces the harm to HH by 12 %. The emissions values associated with ED were 0.0082 and 0.0081 GPt for the BAU and ACR scenarios (Figure 5a). The results imply that mercury release is the main cause of harm to HH. Figure 5b shows the environmental burden for various media, including air, water and land. The impact amounts associated with HH in the BAU scenario were 4.98, 0.07, and 0.07 GPt (emission to air, discharge to water, and release to land), compared to 4.36, 0.07, and 0.08 GPt, in the ACR scenario. Atmospheric mercury emission was the main source of harm to HH. In the context of ED, the mercury emission to air, discharge to water, and release to land in the BAU scenario were 3.16, 0.01, and 5.04 MPt ($1 \text{ MPt} = 1 \times 10^6 \text{ Pt}$), compared to 2.77, 0.01, and 5.35 MPt in the ACR scenario (Figure 5b). Mercury release to land was the largest source of harm to ED (over 5 MPt), followed by mercury emission to air and discharge to water as shown in Figure 5b. In summary, the environmental impact of mercury releases was greater under the BAU than ACR scenario. ACR mainly reduces mercury emission to air, which causes harm to HH. Compared to HH, elemental mercury release to the natural environment has less impact on ED.

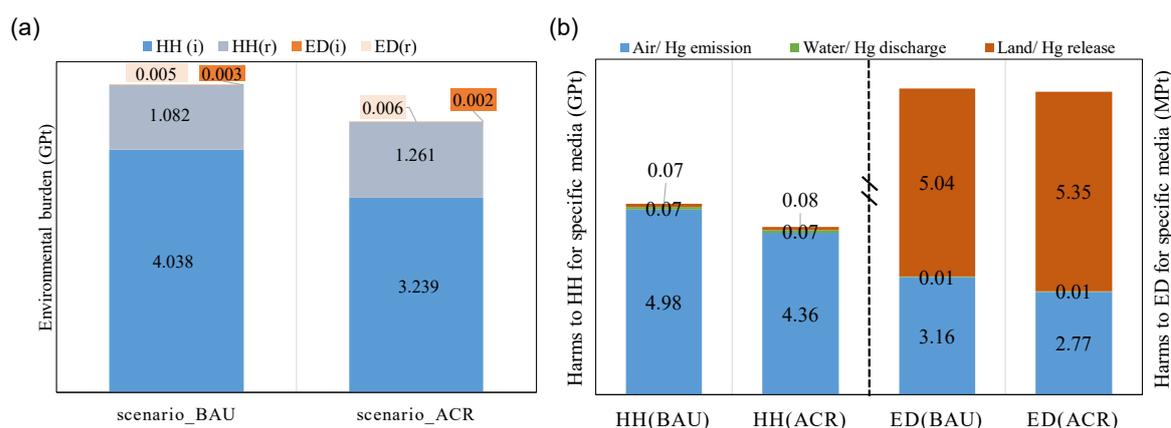


Figure 5: The environmental burden imposed by mercury releases in the two scenarios: (a) overall and (b) for specific media

4. Conclusion

An LCA approach was used to examine the environmental impact of anthropogenic mercury release in China in 2019 based on two scenarios. The total mercury input in 2019 was 2,152 t, of which the total amount released to the natural environment was 840 t under the ACR scenario, which was 44 t lower than in the BAU scenario. Waste treatment and disposal processes, including for both mercury containing general and sector-specific waste, are the major contributors to mercury release to land. The best currently available technologies can reduce the initial distribution of atmospheric emissions, rather than emissions in the redistribution stage.

Applying ACR can reduce harm to human health and marine ecosystems by 12 %. The DALY values under the BAU and ACR scenarios for HT were 1.75×10^5 and 1.53×10^5 DALY. For TET, the values for the BAU and ACR scenarios were 18.8 and 18.6 species/y, while those for FET were 0.013 and 0.013 species/y, and those for MET were 0.052 and 0.046 species/y. The total environmental impact was greater under the BAU (5.13 GPt) than ACR scenario (4.51 GPt), especially the impact on HH. ACR mainly reduces mercury emission to air, which causes harm to HH. Compared to the harm to HH, mercury release to the environment has a smaller impact on

ED. Mercury release to land caused the most harm to ED (over 5 MPt), followed by mercury emission to air and discharge to water. This study provides quantitative information on the environmental impact of mercury release, facilitating strategic management of mercury emissions in line with the MCM (implemented in China in 2017). The limitation of this study is that only elemental mercury was considered for LCIA under the system boundary. Mercury can be reacted either under the treatment/ disposal processes or long time transportation into mercury compounds i.e. methylmercury, gaseous oxidized mercury, and mercuric chloride and so on. However, the environmental impact from such mercury compounds was out of estimation due to a lack of inventories. Future work will focus on quantitative analysis by sub-sources of anthropogenic activities, especially investigating the environmental impact of the release caused by those sub-sources. Clarifying the impacts of mercury pollution is crucial to efforts to reduce those impacts.

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