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Life Cycle Impact Analysis of Anthropogenic Mercury Release in Malaysia

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Anthropogenic activities have aroused great concern in terms of the negative impact on ecosystems and human health. With rapid industrial development, Malaysia has experienced problems with regard to mercury pollution. 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 Malaysia. In this study, inventories for total mercury emission and release in 2019 were devised to understand pollution sources. A life cycle impact assessment was used to identify the major factors contributing to the overall environmental burden. The environmental impact of anthropogenic mercury releases was compared between (sub)source categories. The total mercury input in 2019 was 36.4 t, of which 30.4 t were released to the natural environment under the output scenario of mercury release with no emission control. The respective amounts of 12.7, 1.8, and 15.9 t of mercury were released to air, water, and land. The environmental burden to terrestrial ecosystem imposed by mercury release was higher than that to freshwater and marine ecosystems. The harm to human health was 4,785 DALY, and harm to ecosystem was 0.85 species/y. The category of coal combustion was the largest contributor to the harms of human health (44 % of total impact), followed by cement production (11 % of total impact), and natural gas extraction and combustion (11 % of total impact). The category of gold mining (no amalgamation) was the largest contributor to the harms to ecosystems (76 % of total impact), followed by coal combustion (11 % of total impact). The result of this study can provide a scientific information to policymaker for strategic management of mercury in Malaysia.

1. Introduction

Mercury is known as a pollutant element and its compounds remain high toxicity. The global inventory of mercury emissions to the atmosphere from anthropogenic sources in 2015 is estimated to be 2,220 t (UN Environment, 2019). Anthropogenic activities have aroused great concern in terms of the negative impact on the natural environment and human health (Habuer et al., 2018). With rapid industrial development, Malaysia has experienced environmental burden with regard to mercury pollution. High mercury hair concentrations among children have been reported in Malaysia, i.e. a total of 14.4 % of the respondents exceeded the USEPA reference dose (1 ug/g), while 1.86 % of the respondents exceed the World Health Organization (WHO) safe level of 2 ug/g (Samad et al., 2017). High concentration of mercury had been detected in biological organism in the Estuary of Muar River, West Johor, Malaysia (Rahman et al., 2016). Mercury is also contained in tropical fruits duo to agrochemical and fertilizer usage (Praveena et al., 2013). Public concern over the potential risks posed by mercury and its compounds has been increasing. To protect human health and the ecosystems from adverse effects of mercury, Minamata Convention on Mercury (MCM) was signed by Malaysian government on September 24, 2014, and implemented on August, 2017. 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 Malaysia. Extensive research has examined issues associated with the toxicity of mercury and mercury compounds worldwide, including their negative impacts on ecosystems and human health (Rodrigues et al., 2019). Inventories of air (Habuer et al., 2021), water (Tong et al. 2013), and land (Ying et al., 2017) emission and releases, particularly atmospheric emissions, have received much attention globally. The environmental

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performance of mercury-containing goods, such as end-of-life electronic products (Habuer et al., 2017), 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 metal mercury releases resulted in anthropogenic sources has been observed, especially for Malaysia. The objective of this study was to obtain quantitative data on the environmental burden of mercury releases, to facilitate strategic management thereof as the MCM is implemented in Malaysia. To address this issue and provide scientific information for policymakers, this study adopted the LCA approach. Inventories for total mercury emission and release in 2019 were devised to understand pollution sources. 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 (sub)source categories. The result of this study provide a scientific information to policymaker for strategic management on mercury in Malaysia.

2. Materials and methods

2.1 Sources on mercury release

Anthropogenic mercury release sources should be varying depend on different region or country. In that sense, identifying the sources of mercury release, Minamata Convention Initial Assessment (MIA) Report in Malaysia (MEWM, 2021) and a past study (Habuer et al., 2016) were referred in this study. The sources can be identified five source categories of anthropogenic mercury release, extraction and combustion (C1), mineral production (C2), secondary metal production (C3), waste treatment (C4), and crematoria and cemeteries (Table 1); and 21 subsources.

Table 1: Sources of anthropogenic mercury release in Malaysia

C1 Extraction and combustion	C2 Mineral production	C3 Secondary metal production	C4 Waste treatment	C5 Crematoria and cemeteries
C1.1 Coal combustion (1)	C2.1 Non-ferrous metal (bauxite) (1)	C3.1 Production of recycled ferrous metals (1)	C4.1 Incineration of MSW[1)] (1)	C5.1 Crematoria (1)
C1.2 Oil extraction, refinery and use (4)	C2.2 Gold mining (no amalgamation) (1)		C4.2 Incineration of medical waste (1)	C5.2 Cemeteries (1)
C1.3 Natural gas extraction and combustion (2)	C2.3 Cement (1)		C4.3 Incineration of hazardous waste (1)	
C1.4 Biomass power station (1)	C2.4 Ferrous metal (1)		C4.4 Controlled landfills of MSW (1)	
	C2.5 Pulp and paper (1)			
	C2.6 Lime (1)			

Note: The numbers in parentheses indicate the numbers of subcategories. [1)] Municipal solid waste.

2.2 System boundary

Figure 1 shows the system boundary for the LCIA of anthropogenic mercury release in Malaysia. The total mercury input is a sum of mercury release of five source categories as shown in Table 1. A distribution model considering the output scenario (OS) using the predetermined distribution factors provided in UNEP Toolkit Level 2 (UNEP chemicals, 2011). An OS distributed mercury among various sinks and intermediate reservoirs, including air, water, land, wastes (include mercury-containing general waste and sector specific treatment/disposal waste), and stocks. The term “stock” implies mercury is stored in product/by-products/impurities due to a delay of 1 year (y) or more in disposal or treatment (Habuer et al., 2021). Total mercury release (output) to the natural 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. The potential release of each source category estimated using activity rate data and input factor. The input factors were applied the predetermined values given in UNEP Toolkit Level 2. Activity rate data were obtained from various sources including world mineral and energy databases, Malaysian national report (MEWM, 2021) and statistics, published papers. The detailed calculation method for the inventories is reported elsewhere (Habuer et al., 2016).

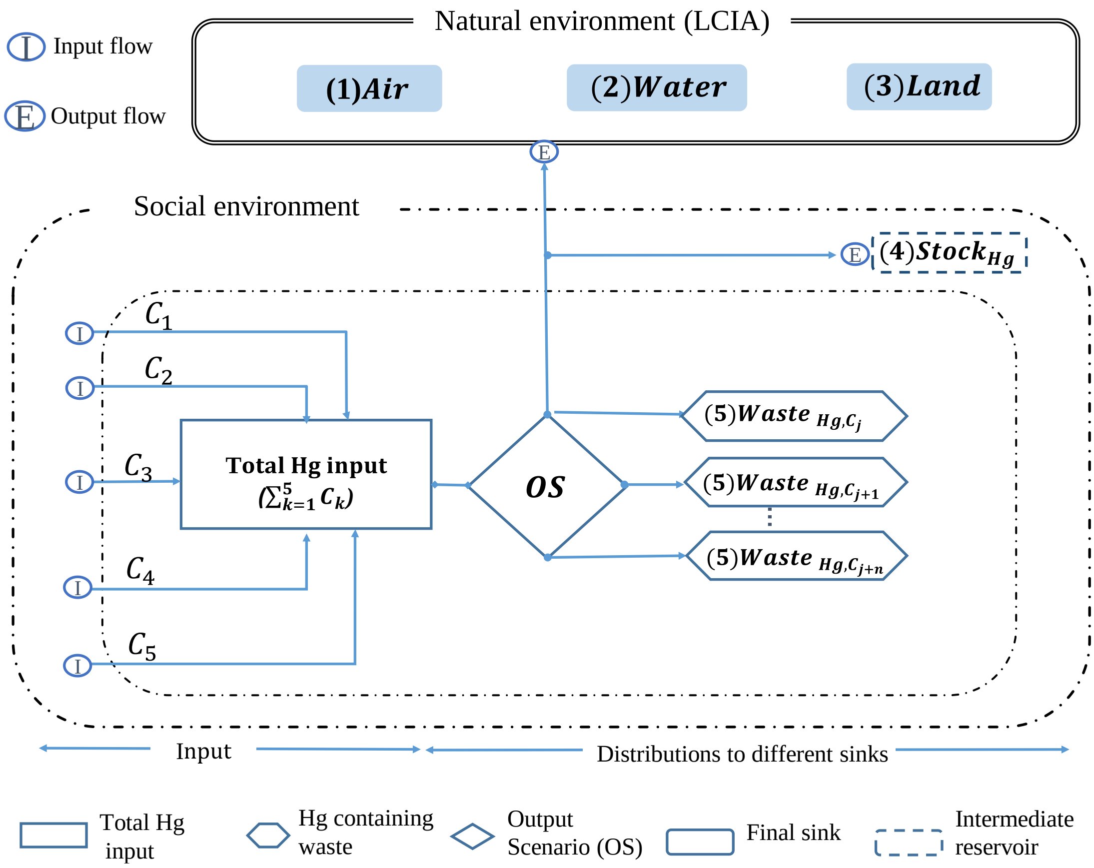


Figure 1: System boundary for LCIA of anthropogenic mercury release in Malaysia

2.3 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 indicators, and an average weighting set. The most authoritative method was selected for the LCIA here. The ReCiPe 2016 converts many LCI results into a few indicator scores that represent the severity of the environmental impact; 18 midpoint indicators and 3 endpoint indicators can be obtained. However, 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)] in the ReCiPe Endpoint (H) (Table 2). 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 21 subcategories.

Table 2: impact and damage categories related to this study

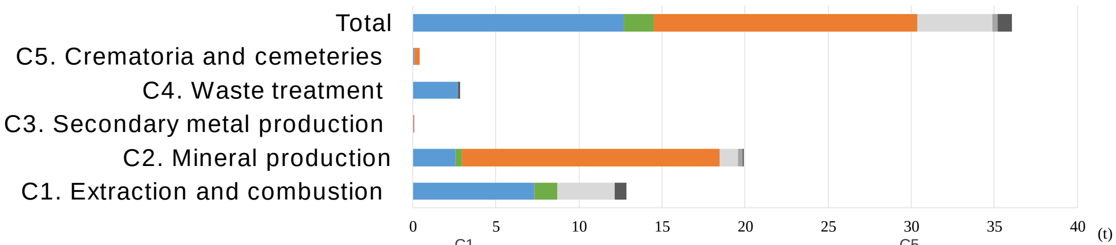
Area of protection	Impact categories	Damage categories	Units
Human health	Human toxicity (HT)	Damage to human health (HH)	Disability-adjusted loss of life years (DALY, years) [1)]
Natural environment	Terrestrial ecotoxicity (TET) Freshwater ecotoxicity (FET) Marine ecotoxicity (MET)	Damage to ecosystem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

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

3. Results and discussion

3.1 Life cycle inventory

The total mercury input in 2019 was 36.4 t, of which 30.4 t were released to the natural environment under the OS of mercury release with no emission control (Figure 2). The respective amounts of 12.7, 1.8, and 15.9 t were released to air, water, and land. In social environments, 4.5 t of mercury was stocked in products/by-products/impurities due to a delay of 1 y or more in disposal or treatment. The respective amount of 0.3 t and 0.9 t of mercury contained either in general waste or sector specific treatment/disposal. The category of mineral production (19.9 t) was the largest contributor to anthropogenic release of mercury in Malaysia, followed by extraction and combustion (12.8 t), waste treatment (2.8 t), crematoria and cemeteries (0.4 t), and secondary metal production (0.07 t).



	C1. Extraction and combustion	C2. Mineral production	C3. Secondary metal production	C4. Waste treatment	C5. Crematoria and cemeteries	Total
Air	7.32	2.56	0.02	2.71	0.10	12.72
Water	1.39	0.39	0.00	0.00	0.00	1.78
Land	0.00	15.53	0.02	0.00	0.33	15.87
Stock	3.43	1.08	0.00	0.00	0.00	4.51
General waste	0.00	0.30	0.02	0.00	0.00	0.32
Specific treatment/disposal	0.70	0.06	0.00	0.13	0.00	0.88

Figure 2: Mercury release of five source categories in Malaysia in 2019

It was reported that the total anthropogenic mercury input in Malaysia in 2012 ranged from 7.6 to 38.09 t (Habuer et al., 2016). According to MIA report in Malaysia (MEWM, 2021), the total input was 32.5 t, in which 9.0 t emitted to Air, 2.6 t discharged to Water, and 14.9 t released to Land in 2014. According to Global Mercury Assessment 2018 (AMAP/UN Environment, 2019), the estimation amount to air was ranged from 3.2 to 24.5 t, with average of 8.3 t in 2015 in Malaysia. The amount of atmospheric emission in this study was larger than that in MIA report in Malaysia, mainly caused by the increased amount of coal combustion in 2019.

3.2 Environmental burden reflected in impact and damage categories

This study analysed the effects of metal mercury releases on the environment, as reflected in impact categories, using ReCiPe (H) v1.1. For TET, the values were 0.85, compared to 0.0002 and 0.001 species/y for FET and MET. The environmental burden to terrestrial ecosystem imposed by mercury release was higher than that to freshwater and marine ecosystems. The harm to human health was 4,785 DALY. It implies that mercury release in Malaysia contributed 4,785 DALY for world population in 2019, and health impact is 0.62 DALYs/ 100,000 people which is 0.14 % of Malaria impact to health. The harm to ecosystem was 0.85 species/y. Figure 3 shows the environmental burden in impact and damage categories imposed by mercury releases from five source categories. For HT, FET, and MET, the category of extraction and combustion was the largest contributor, accounting for 56 %, 53 %, and 54 % of total environmental burden. For TET, the category of mineral production was the largest contributor, accounting for 80 % of total environmental burden (Figure 3a). The environmental burden, as reflected in damage categories, manifested as harm to HH and ED based on normalization of the eco point (Pt). The harm to HH in total was 140 MPt, and that to ED was 0.37 MPt (1 MPt = 1 x 10^6 Pt). It implies that the environmental burden to HH imposed by anthropogenic mercury release is much larger than that to ED. In the harm to HH, the category of extraction and combustion (78.6 MPt) was the largest contributor accounting for 56.1 % of total impact, followed by mineral production (22.4 %), waste treatment (20.6 %), crematoria and cemeteries (0.8 %), and secondary metal production (0.2 %). In the harm to ED, the category of mineral production (0.3 MPt) was the largest contributor accounting for 79.8 % of total impact, followed by of extraction and combustion (13.4 %), waste treatment (4.9 %), crematoria and cemeteries (1.8 %), and secondary metal production (0.1 %) (Figure 3b).

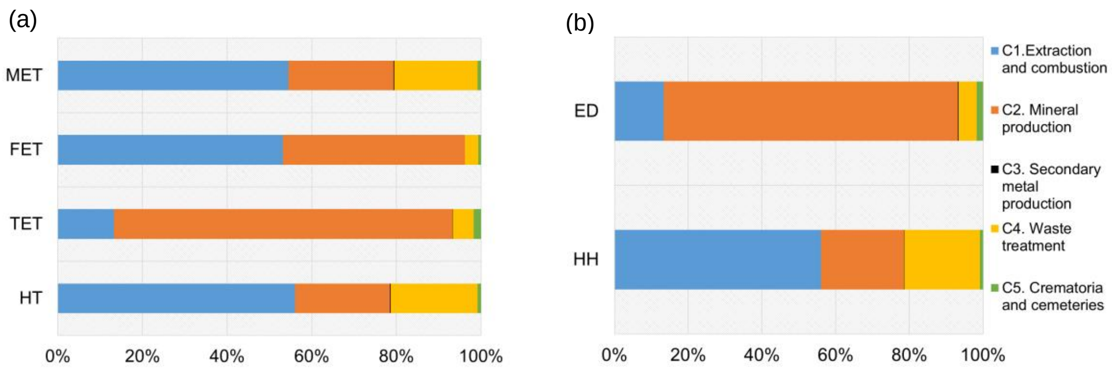


Figure 3: The environmental burden imposed by mercury releases from five source categories reflected as: (a) impact and (b) damage categories

Figure 4 shows the environmental burden imposed by mercury releases from subsource categories. The category of coal combustion was the largest contributor to the harms of marine ecosystem (0.003 MPt, 42 % of total impact) and human toxicity (62 MPt, 44 % of total impact). The category of natural gas extraction and combustion was the largest contributor to the harms of freshwater ecosystem (4.96E-05 MPt, 46 % of total impact), followed by of gold mining (no amalgamation). For the harm to terrestrial ecosystem, the category of gold mining (no amalgamation) was the largest contributor (0.28 MPt, 76 % of total impact) (Figure 4a). The category of coal combustion was the largest contributor to the harms HH (44 % of total impact), followed by cement production (15 MPt, 11 % of total impact), and natural gas extraction and combustion (15 MPt, 11 % of total impact). The category of gold mining (no amalgamation) was the largest contributor to the harms ED (0.28 MPt, 76 % of total impact), followed by coal combustion (11 % of total impact) shown in Figure 4b.

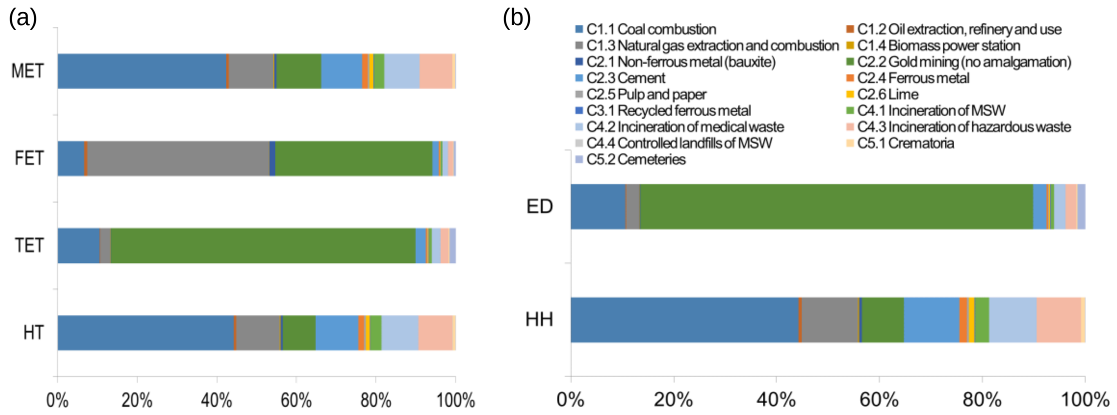


Figure 4: The environmental burden imposed by mercury releases from subsource categories reflected as: (a) impact and (b) damage categories

4. Conclusion

An LCA approach was used to examine the environmental impact of anthropogenic mercury release in Malaysia in 2019. The total mercury input in 2019 was 36.4 t, of which 30.4 t were released to the natural environment under the output scenario of mercury release with no emission control. The respective amounts of 12.7, 1.8, and 15.9 t of were released to air, water, and land. The environmental burden to terrestrial ecosystem imposed by mercury release was higher than that to freshwater and marine ecosystems. The harm to human health was 4,785 DALY, and harm to ecosystem was 0.85 species/y. The category of coal combustion was the largest contributor to the harms of human health (44 % of total impact), followed by cement production (11 % of total impact), and natural gas extraction and combustion (11 % of total impact). The category of gold mining (no amalgamation) was the largest contributor to the harms to ecosystems (76 % of total impact), followed by coal combustion (11 % of total impact). 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

Malaysia in 2017). The limitation of this study is that only metal 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. The environmental impact from such mercury compounds was out of estimation due to a lack of inventories. The harms to ecosystem from mercury compounds might be larger than that from metal mercury. By contrast, the harm to human health from metal mercury might be larger than that from mercury compounds. Future work will focus on the environmental impact of the mercury release in different OSs.

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References

Busto Y., Palacios E. W., Tack F. M. G., Peralta L. M., Cabrera X., Dominguez E. R., Rios L. M., 2015, Environmental Assessment of Remediation Technologies for Mercury Containing Wastes Using LCA Approach, Chemical Engineering Transaction, 45, 433-438.

Gavilan-Garcia I. C., Fernandez-Villagomez G., Gavilan-Garcia A., Alcantara-Concepcion V., 2015, Alternatives of Management and Disposal for Mercury Thermometers at the End of Their Life from Mexican Health Care Institutions, Journal of Cleaner Production, 86, 118-124.

Habuer, Nakatani J., Moriguchi Y., 2017, Resource-availability scenario analysis for formal and informal recycling of end-of-life electrical and electronic equipment in China, Journal of Material Cycles and Waste Management, 19 (2), 599-611.

Habuer, Fujiwara T., Takaoka M., 2021, Anthropogenic Mercury Release Flow in China, Chemical Engineering Transaction, 83, 7-13.

Habuer, Zhou Y. J., Takaoka M., 2018, Time-Series Analysis of Excess Mercury in China, Journal of Material Cycles and Waste Management, 20 (3), 1483-1498.

Habuer, Yoshimoto N., Takaoka M., Fujimori T., Oshita K., Sakai N., Kdir S. A. S. A., 2016, Substance flow analysis of mercury in Malaysia, Atmospheric Pollution Research, 7, 799-807.

Khongprom P., Champanoi S., Suwanmanee U., 2020, An Input-Output Approach for Environmental Life Cycle Assessment of Cement Production, Chemical Engineering Transactions, 81, 1345-1350.

Ministry of Environment and Water Malaysia (MEWM), 2021, Minamata Convention Initial Assessment Report in Malaysia, published by Ministry of Environment and Water, Putrajaya, Malaysia.

Praveena S.M., de Burbure C., Aris A. Z., Hashim Z., 2013, Mini review of mercury contamination in environment and human with an emphasis on Malaysia: status and needs, Reviews on Environmental Health 28 (4), 195-202.

Qi C. C., Ma X. T., Wang M., Ye L. P., Yang Y., Hong J. L., 2017, A Case Study on the Life Cycle Assessment of Recycling Industrial Mercury-Containing Waste, Journal of Cleaner Production, 161, 382-389.

Rahman, M. M., Ansary R. H., Fuad M. M., Kamaruzzaman B. Y., NikW. B. W., 2016, Mercury Determination in Biological Organism in the Estuary of Muar River, West Johor, Malaysia, Oriental Journal of Chemistry,32(5), 2685-2691.

Rodrigues P. D., Ferrari R. G., dos Santos L. N., Conte C. A., 2019, Mercury in Aquatic Fauna Contamination: A Systematic Review on Its Dynamics and Potential Health Risks, Journal of Environmental Sciences, 84, 205-218.

Samad, N. I. A., Isa Z. M., Hod R., 2017, Mercury Hair Concentration among Primary School Children in Malaysia, Children-Basel, 4(12), 109.

Tan Q. Y., Song Q. B., Li J. H., 2015, The Environmental Performance of Fluorescent Lamps in China, Assessed with the LCA Method, International Journal of Life Cycle Assessment 20 (6), 807-818.

Tong Y. D., Zhang W., Hu D., Ou L. B., Hu X. D., Yang T. J., Wei W., Ju L., Wang X. J., 2013, Behavior of Mercury in an Urban River and Its Accumulation in Aquatic Plants, Environmental Earth Sciences, 68 (4), 1089-1097.

UNEP (United Nations Environment Programme) chemicals, 2011, Toolkit for Identification and Quantification of Mercury Releases, Reference Report and Revised Inventory Level 2 Report, Geneva, Switzerland.

UN Environment, 2019, Global Mercury Assessment 2018, UN Environment Programme, Chemicals and Health Branch Geneva, Switzerland

AMAP/UN Environment, 2019, Technical Background Report for the Global Mercury Assessment 2018, Arctic Monitoring and Assessment Programme, Oslo, Norway/UN Environment Programme, Chemicals and Health Branch, Geneva, Switzerland.

Ying, H., Deng M. H., Li T. Q., Jan J. P. G., Chen Q. Q., Yang X. E., He Z. L., 2017, Anthropogenic Mercury Emissions from 1980 to 2012 in China, Environmental Pollution, 226, 230-239.