CHEMICAL ENGINEERING TRANSACTIONS
VOL. 113, 2024
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Jeng Shiun Lim, Bohong Wang, Guo Ren Mong, Petar S. Varbanov

ISBN 979-12-81206-14-4; **ISSN** 2283-9216
DOI: 10.3303/CET24113057

Toxicity and Damage Potential of Atmospheric Mercury Emissions from the Cement Industry in Japan

Habuer

Okayama University, 3-1-1 Tsushima Naka Kita-Ku, Okayama 700-8530, Japan
habuer@okayama-u.ac.jp

Japan has made considerable efforts to minimise mercury use in products and manufacturing processes. Even if Japan emits less mercury into the atmosphere than other countries or regions, its potential toxicity to human health and ecosystems through long-term transport and accumulation remains unknown. Furthermore, there are opportunities to further reduce emissions, especially from large sources like cement plants. The lack of evaluations of the environmental burden of mercury from the perspective of its life cycle has led to observations of anthropogenic sources in Japan. This study compared atmospheric mercury emissions by the cement industry before and after the Minamata Convention on Mercury (hereafter called "Convention") from 2014 to 2020 and explored the time-series human and ecosystem toxicity potentials. The atmospheric mercury emissions from cement production were essentially unchanged during 2014–2018, at around 5.5 t/y. They decreased dramatically to 4.5 t in 2019 and 3.2 t in 2020. Since 2019, the ecosystem, carcinogenic and non-carcinogenic human toxicity impacts of mercury have decreased; the toxicity potential in 2020 was 58.2 % of that in 2014. The potential damage to humans in Japan contributed 9.41 disability-adjusted loss of life years (DALY) to the world population in 2020, which equalled 0.00004 % of the impact of malaria on human health and 0.00002 % of that of traffic accidents. The harm to ecosystem diversity was 0.025 species lost in 2020. The framework of this study is valuable as a systematic evaluation of the effectiveness of strategic mercury management in countries facing similar problems.

1. Introduction

The combination of anthropogenic activities and long-term atmospheric transport has increased global mercury concentrations in the air, water and land (Habuer et al., 2021a). Mercury accumulation can have major effects on human health and the natural environment. The Convention, a global treaty to protect human health and the environment, was adopted on the initiative of the Japanese government and entered into force in August 2017. Countries that sign the treaty are required to control and reduce total mercury emission to the atmosphere; take measures that combine multiple methods to update and replace outdated systems to avoid and reduce mercury pollution (UNEP, 2013). Thus, the mercury management policies in each signing country have required large adjustments. To evaluate the effectiveness of the Convention, it is necessary to develop an approach for assessing the changes in total output on mercury emissions and release and their environmental impact.
Japan experienced Minamata disease outbreaks, caused by organic mercury poisoning, in Kumamoto and Niigata Prefectures during the 1950s and 1960s (Habuer et al., 2021a). Subsequently, Japan has made considerable efforts to minimise mercury use in products and manufacturing processes (Takaoka, 2015). About 80 t of mercury enters Japan annually, of which 52 t is recovered and 11–24 t is disposed of in landfills (Takaoka, 2015). The Ministry of the Environment of Japan (MOEJ) estimated that the atmospheric mercury emissions from anthropogenic sources were 16–21 t in 2010, 16–17 t per year in 2014–2018, 14.4 t in 2019 and 9.4 t in 2020 (MOEJ Atmospheric Mercury Emission Inventory Database, 2010–2020). Cement production plants account for 42 % of emissions, followed by waste incineration facilities (37 %), coal-fired power plants and industrial boilers (11 %) and non-ferrous metal smelting plants (10 %). Although Japan emits less atmospheric mercury than other countries, such as China (Habuer et al., 2021a) and Malaysia (Habuer et al., 2021b), its potential toxicity to human health and the ecosystem through long-term transport and accumulation is unknown.

Paper Received: 27 May 2024; Revised: 5 September 2024; Accepted: 30 October 2024
Please cite this article as: Habuer H., 2024, Toxicity and Damage Potential of Atmospheric Mercury Emissions from the Cement Industry in Japan, Chemical Engineering Transactions, 113, 337-342 DOI:10.3303/CET24113057

Furthermore, there are opportunities to further reduce atmospheric mercury emissions, especially from large emission sources such as cement plants.

Worldwide, many recent studies have explored the toxicity of mercury and mercury compounds. Increasing attention has been paid to flow and inventory analyses of mercury (Habuer et al., 2021a), mercury-containing goods (Hannah et al., 2014) and byproducts (Cai et al., 2020). For instance, Hannah et al. (2014) presented a global inventory of commercial mercury uses and releases into the air, water, soil and landfills from 1850 to 2010. Wu et al. (2018) explored the options for coal-fired power plants, coal-fired industrial boilers, nonferrous metal smelting, waste incineration and cement clinker production by considering the reduction potential and impact of future technology changes in China in 2015, and forecast future emissions for 2020, 2025 and 2030. Cai et al. (2020) compiled high-spatiotemporal-resolution atmospheric mercury emission inventories for Chinese cement plants using the mass balance method and input–output data and showed that mercury emissions increased from 80 to 113 t due to the rapid expansion of production and kiln-type substitution in 2007–2015. Researchers have also taken interest in the method associated with environmental impact assessment from a life cycle perspective, which is called life cycle impact assessment (LCIA). For example, Habuer et al. (2021b) conducted a LCIA of anthropogenic mercury release in Malaysia. Ahmed et al. (2016) assessed the environmental impact of the Egyptian cement industry based on a LCIA. Zhang and Pushpalal (2012) presented a comparative study of the LCIA of different life cycle inventories for the cement industry in China for 2008. The results of such studies indicate that controlling the forms and total mercury emissions and release are crucial for environmental protection and human health. As the Convention enters the implementation phase, further information and insights from scientific studies are needed to support government decision-making and management. Few studies in Japan have evaluated either the effectiveness of the Convention from a life cycle perspective or the environmental burden resulting from anthropogenic sources. The present study addresses this need by comparing atmospheric mercury emissions from the cement industry before and after the Convention and exploring time-series human and ecosystem toxicity potentials. The findings will help facilitate the creation of strategic management policies and systematic evaluations of the effectiveness of the Convention in countries facing similar problems.

2. Methodology

The status of the cement industry in Japan, including its distribution, annual capacity and mercury emissions, was visualised using the collected data. The toxicity and damage potential of atmospheric mercury emissions in the cement industry were identified through a LCIA.

2.1 Data collection

The distribution and capacity of cement plants in Japan were extracted from a Japan Cement Association (JCA) report and JCA Statistics (2023). The time series of cement production was obtained from the JCA Statistics Database (2023). Atmospheric mercury emission data were collected from the Atmospheric Mercury Emission Inventory Database of the Ministry of Environment, Japan (MOEJ Atmospheric Mercury Emission Inventory Database, 2014–2020). The Quantum Geographic Information System (QGIS), an open-source, cross-platform geographic information system, was used to identify the locations of cement plants in Japan (Figure 1).

2.2 Life cycle impact assessment

LCIA is commonly used for assessing the environmental impact of a process (Gavilan-Garcia et al., 2015). ReCiPe is the most widely used environmental impact assessment method and covers all stages, including classification, characterisation, damage assessment, normalisation and weighting (Habuer et al., 2021b). Therefore, the method ReCiPe Midpoint and Endpoint (H) with World (2010) H V1.07 (RIVM, 2017) were used for the LCIA. According to Habuer et al. (2021b), negative impacts of mercury can be classified as human toxicity (HT), terrestrial toxicity (TET), freshwater toxicity (FET), and marine ecotoxicity (MET) at the midpoint, and damage to human health (HH) and ecosystem diversity (ED) at the endpoint. The toxicity and damage potential at the mid- and endpoints can be calculated using Eq(1) and Eq(2).

$$TP_{Hg,m} = \sum_i E_{Hg,i} \times CF_{m,air,i} \tag{1}$$

$$DP_{Hg,e} = \begin{cases} \sum_m TP_{Hg,m} \times F_{m\rightarrow,\mathrm{e}} & ,if\ e = ED \\ TP_{Hg,m} \times F_{m\rightarrow,\mathrm{e}} & ,if\ e = HH \end{cases} \tag{2}$$

Here, $TP_{Hg,m}$ is the toxicity potential of mercury emissions in the midpoint impact category (m). $DP_{Hg,e}$ is the damage potential of mercury emissions in the endpoint impact category (e). $E_{Hg,i}$ is the amount of atmospheric mercury emissions of form i in the intervention air. The form of metallic mercury i in the atmosphere was hypothesised to be 50 % vaporised mercury and 50 % mercury compounds (Habuer and Fujiwara, 2024). $CF_{m,air,i}$ is the characterisation factor that connects intervention air with the midpoint impact category (m). $F_{m\rightarrow,e}$ is the mid- to endpoint conversion factor. The chemical 1,4-dichlorobenzene (1,4-DCB) was used as a reference substance in the midpoint calculation (in urban air, freshwater and seawater for HT, FET and MET, respectively). The damage to HH is the total *DALY*. The damage to ED is given as species lost over time (*species/year*). Atmospheric emissions from cement plants were defined as the system boundary for the LCIA, and the total emissions in 1 y was the functional unit.

3. Results and discussion

3.1 Distribution and capacity of cement plants

In April 2023, cement was produced in Japan in 28 plants owned by 16 companies, with an annual clinker production capacity of 53 × 10^6 t (JCA Statistics, 2023). Figure 1 shows the locations of cement plants in Japan. There is a relatively high density in Kyushu (six plants) and Yamaguchi Prefecture (four plants); both areas have rich limestone resources. There are five plants in Kanto, which is the largest cement consumption market in Japan (JCA, 2023).

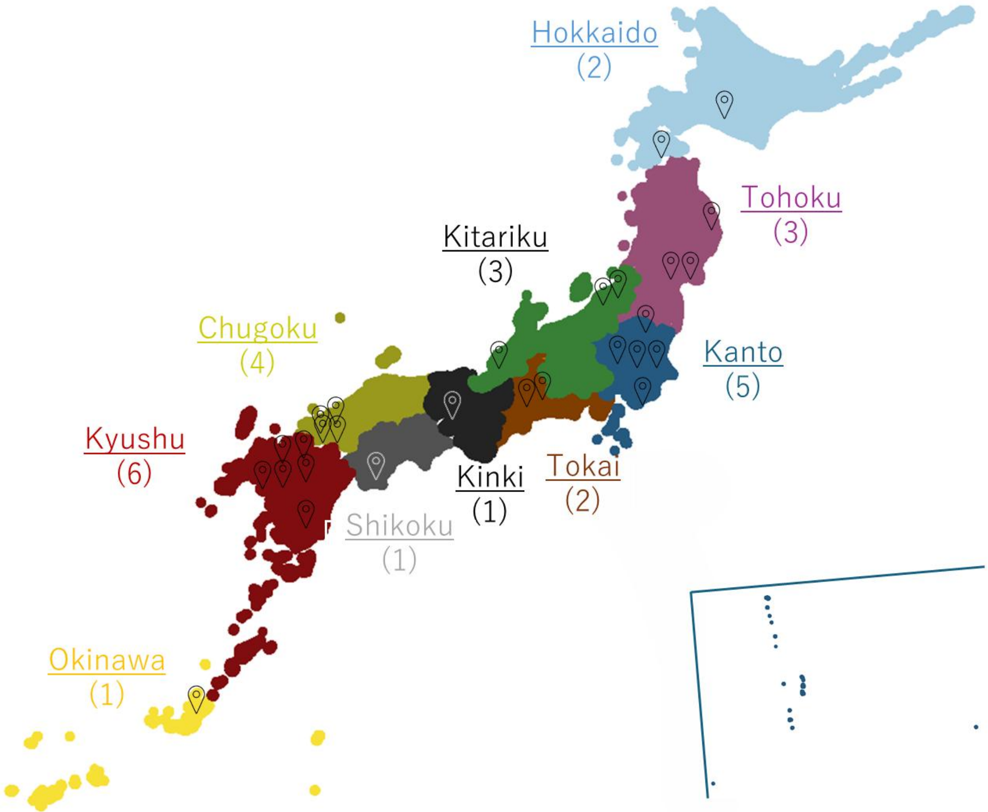

Figure 1: Distribution of cement plants in Japan

The cement production capacity per plant is approximately 1.8 × 10^6 t (JCA Statistics, 2023). Figure 2 shows the annual cement production capacity of each plant based on data for 2023. The largest plant is in Kyushu, with an annual cement production capacity exceeding 6 × 10^6 t; the next two largest plants have annual cement production capacities exceeding 4 × 10^6 t and are located in limestone-rich regions in Kyushu and Chugoku (Figure 2). Two plants with annual cement production capacities exceeding 3 × 10^6 t are located in Shikoku and Hokkaido. While Kanto is the largest cement consumption market in Japan and possesses five cement plants, the annual cement production capacity of each plant is less than 2 × 10^6 t (JCA, 2023).

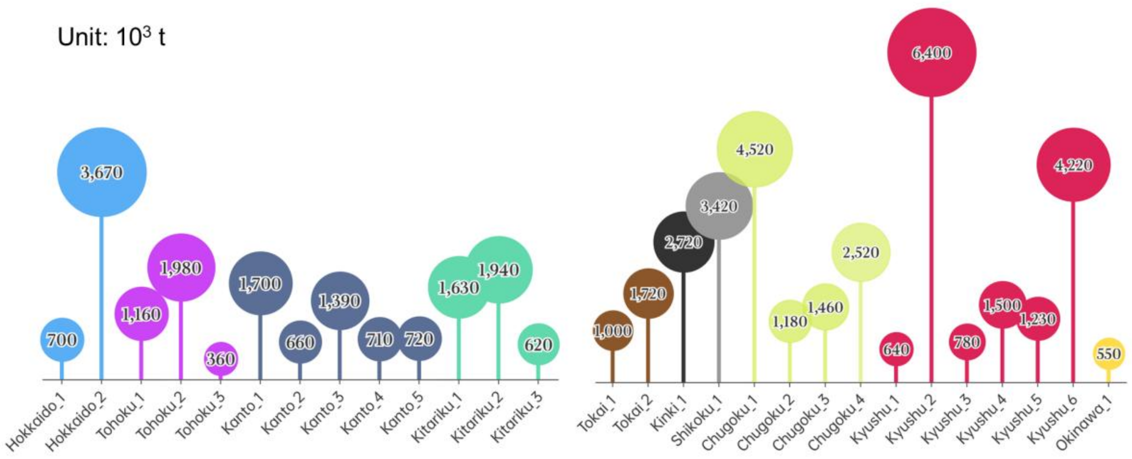

Figure 2: Annual production capacity of the cement plants in Japan (FY2023)

3.2 Atmospheric mercury emission in the cement industry

Figure 3 shows the time-series of cement production and atmospheric mercury emissions in 2014–2020. During 2014–2018, the annual production fluctuated between 61.1 × 10^6 t at most in 2014 and 59.2 × 10^6 t at the least in 2015. With decreasing domestic demand, the cement production decreased to 58 × 10^6 t in 2019 and 56 × 10^6 t in 2020 (JCA Statistics Database, 2023). Portland cement accounted for 75 % of the total annual production and mixed/blended cement for 25 % (JCA Statistics Database, 2023). The atmospheric mercury emissions from cement production were essentially unchanged during 2014–2018, at around 5.5 t/y. They fell dramatically to 4.5 t in 2019 and 3.2 t in 2020 (MOEJ Atmospheric Mercury Emission Inventory Database, 2014–2020) because of the decrease in cement (clinker) production due to the decreasing domestic demand initially and the subsequent requirement to prioritise raw materials and fuels with low mercury contents after implementing the Convention. Note that the atmospheric mercury emissions were estimated using emission factor and activity rate data (annual production) before 2019. From 2019 onward, they were estimated using reports on the mercury concentration in flue gases measured periodically and submitted by operators under the Air Pollution Control Act in Japan (MOEJ Atmospheric Mercury Emission Inventory Database, 2019–2020).

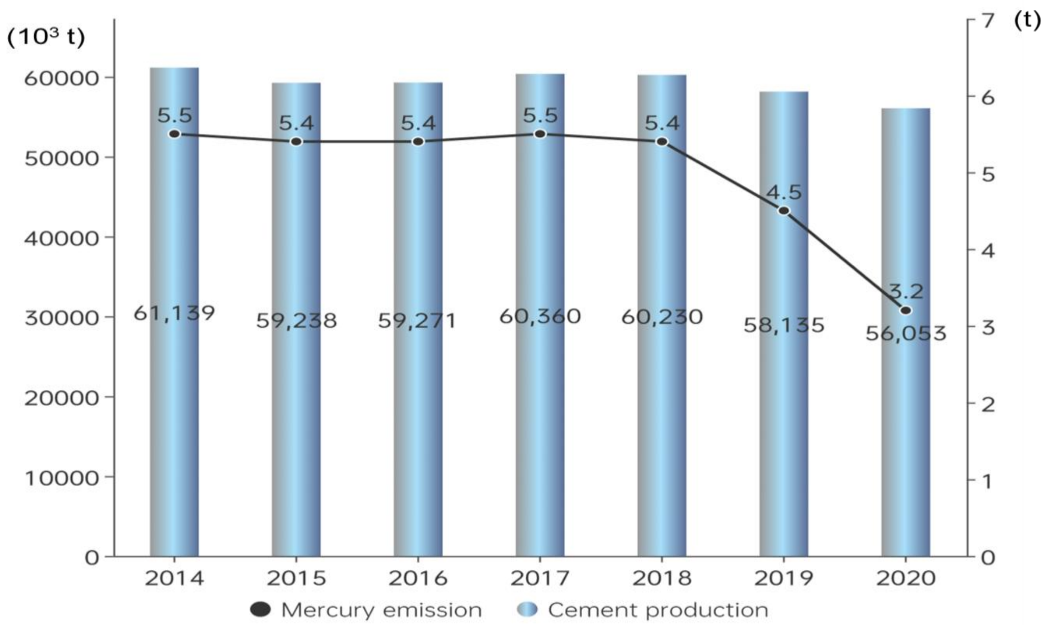

Figure 3: Time-series of annual atmospheric mercury emissions by the cement industry

3.3 Toxicity and damage potential of atmospheric mercury emissions in the cement industry

Table 1 gives the toxicity potential at the midpoint. Since 2019, all impacts of mercury have been decreasing, including TET, FET, MET and carcinogenic and non-carcinogenic HT as the toxicity potential in 2020 was 58.2 % of that in 2014. Comparing the impact categories, the largest impact caused by atmospheric mercury emissions from the cement industry in 2014–2020 was 2.21–3.79 × 10^9 kg 1,4-DCB equivalent (eq.) to terrestrial ecosystems, followed by 3.98–6.84 × 10^7, 3.84–6.60 × 10^5 kg and 1.62–2.78 × 10^3 1,4-DCB eq. to urban air, marine ecosystems and freshwater ecosystems.

Table 1: Characterization of atmospheric mercury emission at the midpoint [units: kg 1,4-DCB]

Impact Category	2014	2015	2016	2017	2018	2019	2020
TET	3.79×10^9	3.73×10^9	3.73×10^9	3.79×10^9	3.73×10^9	3.11×10^9	2.21×10^9
FET	2.78×10^3	2.73×10^3	2.73×10^3	2.78×10^3	2.73×10^3	2.27×10^3	1.62×10^3
MET	6.60×10^5	6.48×10^5	6.48×10^5	6.60×10^5	6.48×10^5	5.40×10^5	3.84×10^5
carcinogenic HT	1.91×10^5	1.88×10^5	1.88×10^5	1.91×10^5	1.88×10^5	1.57×10^5	1.11×10^5
non- carcinogenic HT	6.82×10^7	6.70×10^7	6.70×10^7	6.82×10^7	6.70×10^7	5.58×10^7	3.97×10^7

The damage potential to HH at the endpoint was largest in 2014 (16.2 DALY) and lowest in 2020 (9.41 DALY). The damage to ED at the endpoint was largest in 2014 (0.043 species/y) and lowest in 2020 (0.025 species/y). The damage to HH due to atmospheric mercury emissions from the cement industry exceeded that to ED (Figure 4a), and the total damage decreased from 214,000 in 2014 to 125,000 eco points in 2020 (Figure 4b). The damage potential to humans in Japan contributed 9.41 DALY to the world population in 2020, equalling 0.00004 % of the impact of malaria on human health and 0.00002 % of that due to traffic accidents. The harm to ED was 0.025 species lost over time in 2020.

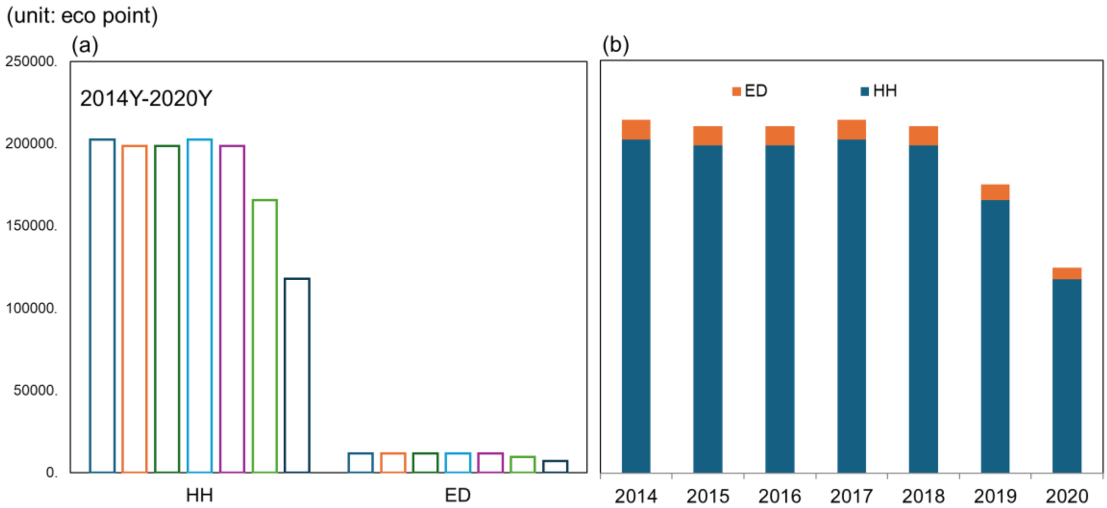

Figure 4: The damage potential of mercury emissions shown as a (a) Weighting and (b) Single score at the endpoint

4. Conclusions

This study compared atmospheric mercury emissions by the cement industry in Japan before and after implementation of the Convention and explored the time-series human and ecosystem toxicity and damage potential in 2014–2020. The atmospheric mercury emissions from cement production were essentially unchanged during 2014–2018, at around 5.5 t/y. They decreased dramatically to 4.5 t in 2019 and 3.2 t in 2020 after the implementation of the Convention. The main reasons for the decreases in emissions after the Convention were decreased cement production and emission reduction measures taken by the cement industry, prioritising raw materials and fuels with low mercury contents. Such mitigation options may appreciably reduce atmospheric mercury emissions in other countries.

Since 2019, all ecosystem toxicity, and carcinogenic and non-carcinogenic human toxicity have decreased; the toxicity potential in 2020 was 58.2 % of that in 2014. The toxicity potential decreased more than the total mercury emissions. The damage potential to humans in Japan contributed 9.41 DALY to the world population in 2020, equalling 0.00004 % of the impact of malaria on human health and 0.00002 % of that due to traffic accidents. The negative impact on ED was 0.025 species lost over time in 2020. One limitation of this study was that details for specific mercury compounds were ignored due to the lack of impact indicators. Further work should focus on other anthropogenic sources of mercury and their reduction potential in Japan.

Acknowledgments

This research was supported by JSPS KAKENHI Grant Numbers JP21K17895. This research was also supported in part by the “Initiative for Realizing Diversity in the Research Environment” from MEXT, Japan. A part of the research was supported by the Okayama University Diversity Promotion Headquarters Gender Equality Office Research Support Project.

References

Ahmed A.M.A., Abdelazim M.N., Mahmoud F.B., Mona G.E.I., Masasaki S., 2016, Environmental impact assessment of the Egyptian cement industry based on a life-cycle assessment approach: a comparative study between Egyptian and Swiss plants, Clean Technologies and Environmental Policy, 18, 1053-1068.

Cai X., Cai B., Zhang H., Chen L., Zhang C., Tong P., Lin H., Zhang Q., Liu M., Tong Y., Wang X., 2020, Establishment of High-Resolution Atmospheric Mercury Emission Inventories for Chinese Cement Plants Based on the Mass Balance Method, Environmental Science & Technology, 54, 13399-13408.

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 (Jan), 118-124.

Habuer, Fujiwara T., Takaoka M., 2021a, The response of anthropogenic mercury release in China to the Minamata Convention on Mercury: a hypothetical expectation, Journal of Cleaner Production, 323, 129089.

Hannah M.H., Daniel J.J., Helen M.A., David G.S., Elsie M. S., 2014, Historical Mercury Releases from Commercial Products: Global Environmental Implications, Environmental Science & Technology, 48, 10242-10250.

Habuer, Abdul Hamid M.N.F.B., Fujiwara T., 2021b, Life Cycle Impact Analysis of Anthropogenic Mercury Release in Malaysia, Chemical Engineering Transactions, 89, 265-270.

Habuer, Fujiwara T., 2024, The applicability of human health damage factors to anthropogenic mercury releases under the life cycle impact assessment, The 19th Meeting of the Institute of Life Cycle Assessment Proceeding, 2-E3-02, the Institute of Life Cycle Assessment, Japan. (in Japanese)

JCA (Japan Cement Association), 2023, Cement industry initiatives following amendments to the Air Pollution Control Law considering the Minamata Convention < www.env.go.jp/council/content/i_06/000170983.pdf> accessed 12.05.2024. (in Japanese)

JCA Statistics, Japan Cement Association, 2023, < www.jcassoc.or.jp/cement/2eng/e_02.html> accessed 22.05.2024.

JCA Statistics Database, Japan Cement Association, 2023, <www.jcassoc.or.jp/cement/3pdf/jh2_1100.pdf> accessed 20.05.2024. (in Japanese)

MOEJ Atmospheric Mercury Emission Inventory Database, Ministry of the Environment Japan, 2010-2020, < www.env.go.jp/air/suigin/invertory.html> accessed 20.05.2024. (in both Japanese and English)

RIVM (Rijksinstituut voor Volksgezondheid en Milieu), 2017, ReCiPe 2016 A harmonized life cycle impact assessment method at midpoint and endpoint level, Report I: Characterization, National Institute for Public Health and the Environment, Bilthoven, The Netherlands.

Takaoka M., 2015, Mercury and mercury-containing waste management in Japan, Journal of Material Cycles and Waste Management, 17, 665-672.

UNEP (United Nations Environment Programme), 2013, Minamata Convention on Mercury, < www.mercu_rycon_vention.org/> accessed 20.04.2024.

Wu Q, Li G, Wang S, Liu K, Hao J., 2018, Mitigation Options of Atmospheric Hg Emissions in China, Environmental Science & Technology, 52(21), 12368-12375.

Zhang W., Pushpalal D., 2012, Life Cycle Environmental Impact Assessment of Air Pollutants and CO2 Emissions from the Cement Industry of China: Regional Analysis Based on CML Method, Journal of Life Cycle Assessment, Japan, 8(2), 181-199. (in Japanese with English abstract)