Assessment of Mercury Pollution and Its Human Health Risk in Myanmar

（ミャンマーにおける水銀汚染とそれに伴うヒトの健康リスクの評価）

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ABSTRACT

Myanmar, a developing country in Southeast Asia, has various mineral and natural resources, such as for jade, gold, ruby, and copper. Recently, population and economic growth in Myanmar has been increasing year by year. Therefore, environmental pollution by chemicals such as metals and pesticide in Myanmar, especially in urban areas is of great concern. For example, mercury (Hg) is listed among the top 10 most harmful metals by the World Health Organization (WHO). However, research conducted on environmental pollution by Hg in Myanmar is very few. Therefore, the objectives of this study were to 1) assess Hg pollution by artisanal and small-scale gold mining (ASGM) in Myanmar in comparison with other Southeast Asian countries, 2) understand contamination status by Hg in urban areas in Myanmar, 3) identify source of Hg in urban areas in Myanmar, and 4) evaluate human health risk by Hg exposure.

Firstly, the study reviewed studies of Hg pollution by ASGM from Myanmar and other Southeast Asian countries. ASGM is the world's fastest-growing source of Hg and can release Hg into the atmosphere, hydrosphere, and geosphere. Mercury has been widely used in ASGM industries throughout Southeast Asia countries, including

Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, and Thailand. Here, 16 relevant studies were systematically searched by performing a PRISMA flow, combining the keywords of “Hg”, “ASGM”, and relevant study areas. Mercury concentrations exceeding WHO and United States Environmental Protection Agency (US EPA) guideline values were reported in environmental (i.e., air, water, and soil) and biomonitoring samples (i.e., plants, fish, and human hair). The findings indicated severe Hg contamination around the ASGM process, specifically the gold-amalgamation stage, was significantly high. To one point, Hg atmospheric concentrations from all observed studies were shown to be extremely high in the vicinity of gold operating areas. ASGM-related health risks by Hg exposure to miners and nonminers were significant and several health impacts including respiratory disorder and neurological effects were reported. For the review study suggested attentions should be given regarding the public health concern, specifically for the vulnerable groups such as adults, pregnant women, and children who live near the ASGM activity. In the future, more research and assessment will be required to investigate the current and evolving situation in ASGM communities.

In recent years, environmental pollution is of great concern in Myanmar due to urbanization and industrialization in urban areas like Yangon and Mandalay. To understand urban pollution by Hg in Myanmar, the study analyzed 39 road dust and 74 sediment samples from urban areas of Yangon and Mandalay and sub-urban areas of Pathein, Chaungtha, Wundwin, and expressway from Yangon to Pathein in Myanmar during 2014 – 2018. Mercury concentration in road dust and sediment from urban areas was significantly higher than that in sub-urban areas. Especially, high pollution was observed in Mandalay. In addition, the ecological risk index estimated by using Hg concentration in sediment showed that Mandalay was considerable risk. Those results

indicate Hg pollution is severe in Mandalay. Compared with other study results, concentration of Hg in road dust and sediment from Myanmar was moderately lower. However, because population in Myanmar is increasing, significant Hg pollution will be occurred in future.

To estimate the source of Hg pollution in urban areas, the principal component analysis (PCA) and positive matrix factorization (PMF) model including other 30 metal concentrations in road dust and sediment were performed. For road dust, Hg was related to aluminum (Al), selenium (Se), cadmium (Cd), cesium (Cs), gadolinium (Gd), and thallium (Tl) and those metals were also significantly higher in urban areas than sub-urban areas, but clear source was not identified. On the other hand, significant correlations of Hg with molybdenum (Mo) and Cd were observed in sediment. Those metals with Cu, tin (Sn), antimony (Sb), and lead (Pb) showed high concentration in urban areas and belonged to same cluster by PCA and PMF, indicating that Hg source in sediment is traffic emission and municipal waste.

As mentioned earlier, Hg pollution was significant in urban areas from Myanmar. Therefore, human health risk in urban areas is of concerened. According to the methods by US EPA, health risk by Hg exposure from road dust in adults and children was estimated. In this study, three routes of ingestion, inhalation, and dermal absorption by skin were considered. For each exposure pathway, Hg exposure levels in adults and children were much lower than the reference dose values. This suggests no harmful effects on human health from Hg exposure up to now.

Keywords: Myanmar, ASGM, road dust, sediment, mercury, heavy metals

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Chapter I General Introduction

1. Introduction

Mercury (Hg) is ranked among the World Health Organization's (WHO) top 10 most detrimental metals, and its various chemical manifestations pose a significant public health issue (McNutt, 2013). All of its have three forms, whether elemental (metallic), inorganic, or organic, exhibit a high degree of toxicity. In particular, methylmercury (MeHg) is the most dangerous form because it can bioaccumulate in microorganisms and biomagnify or enhance the trophic levels in aquatic food webs (Moreno-Brush et al., 2020). Meanwhile, elemental Hg can be converted to MeHg in aquatic sediments.

Due to the increased population in the world, urbanization and industrialization have been extended by human beings. The anthropogenic activities such as mining, smelting, burning of coal-fired, biomass, gas, and oil fuel, mining, petrochemical, construction, municipal waste disposal, and traffic emissions but also natural sources, including local soil parent materials and rocks, can cause major environmental pollution by releasing vast amounts of heavy metals into our surrounding environment (Amato et al., 2011; Li et al., 2001; Okorie et al., 2012). Among the various pollutants, Hg have significant attention due to its toxicity. Different types of Hg such as elemental, inorganic and organic forms can be released into the environment which are atmosphere, water, and terrestrial by human activities. According to the united nation environment program (UNEP), Hg has been released into the atmosphere mostly emitted by 38% of artisanal and small-scale gold mining (ASGM) activities, 21 % of coal combustion, 11 % of cement production, 10 % of non-ferrous metal production, and others such as oil refining, vinyl-chloride monomer production, and waste disposal and incineration and so on (UNEP, 2019). Moreover, ASGM has been occurring in worldwide, with an estimated 16 million miners who afford up to 20 % of the annual gold production (UNEP, 2019).

ASGM processes can be categorized on the basis of region and depend on the gold deposit types such as panning, river mining, suction dredging and hydraulic mining. As an example of common method, gold ore is excavated from the underground mining, after proceeding the dried and grinding, gold particles are collected and a piece of Hg is added to the pan to extract gold by performing gold-Hg amalgam. At last, Hg was vaporized using a burner to obtain the pure gold. Then, Hg can be discharged into the environment.

Myanmar, a developing country in Southeast Asia, has various mineral and natural resources, such as for jade, gold, ruby, and copper. Myanmar has been facing overexploitation of natural resources for more than two decades because its people seek to extract its natural resources illegally (Htun, 2014). Additionally, 70% of the population of Myanmar is in rural areas and rely on natural resources. However, growing population and urbanization have recently occurred in major cities like Yangon and Mandalay in Myanmar. Consequently, there are many factors that we should consider such as industrial emissions which can lead to the release of pollutants into the air and water, vehicular emissions which can cause pollution due to exhaust emissions, particularly in major cities like Yangon and Mandalay. Furthermore, improper waste practices and incineration can have concerns due to the release of harmful pollutants and toxins into the atmosphere and surrounding environment such as soil, road dust, and sediment. Finally, the consequences of urban pollution can lead to the human health concerns such as respiratory issues, cardiovascular diseases, cancer risks, neurodevelopmental impacts, mental health concerns, and disparities among vulnerable groups including women and children.

Therefore, the objective of this study is to understand the Hg contamination status in Myanmar from ASGM and also, from the urban area of Yangon and Suburban areas and

suburban areas of Wundwin, Pathein, Expressway (from Pathein to Yangon), Chaungtha, and Wundwin. The overall objectives of the study have two parts and are as follows:

Part I: Mercury pollution in ASGM

1. To evaluate Hg contamination in environmental media and the risks of Hg exposure on human health from ASGM
2. To propose a relevant policy framework regarding Hg issues

Part II: Mercury contamination in urban and suburban areas

3. To understand contamination status by Hg
4. To estimate sources of Hg contaminations by contributing with other metals
5. To assess human health risk by Hg exposures

Chapter II
Hg Pollution from Artisanal and Small-scale Gold Mining in Myanmar and other Southeast Asian Countries

1. Introduction

1.1. Mercury

Mercury (Hg) is listed among the top 10 most harmful metals by the World Health Organization (WHO), and its chemical forms are considered a public health concern (McNutt, 2013). All its common forms, including elemental (metallic), inorganic, and organic are highly toxic. In particular, methylmercury (MeHg) is the most dangerous form because it can bioaccumulate in microorganisms and biomagnify or enhance the trophic levels in aquatic food webs (Moreno-Brush et al., 2020). Meanwhile, elemental Hg can be converted to MeHg in aquatic sediments. The use of elemental Hg in ASGM sector can be hazardous because of the inhalation of Hg vapor, which easily penetrates the blood–brain barrier and induces neurotoxicity (Harada, 1995). A famous catastrophic Hg outbreak occurred in Minamata Bay, Japan, in the 1950s, when wastewater containing MeHg from a factory was discharged into the Shiranui Sea, poisoning the people who ingested the contaminated seafood (Harada, 1995). This became one of the first and the most critical incidents of Hg poisoning due to an industrial site.

Different forms of Hg can be released into the atmosphere, water, and across land as a result of human activities such as burning of fossil fuels (e.g., coal and petroleum), industrial effluents, product waste (e.g., electronic) from intentional use, dental amalgamation, agricultural practices, and ASGM and natural processes, including volcanic eruptions, rock weathering, and forest fires. Thus, Hg is discharged worldwide into the environments. ASGM is the world's fastest-growing source of Hg and can discharge Hg into both the aquatic environment and the terrestrial ecosystem. The emission of Hg into the atmosphere via ASGM account for 37.7% of global outputs among the other Hg emission sources, with South America, Asia, and Sub-Saharan Africa

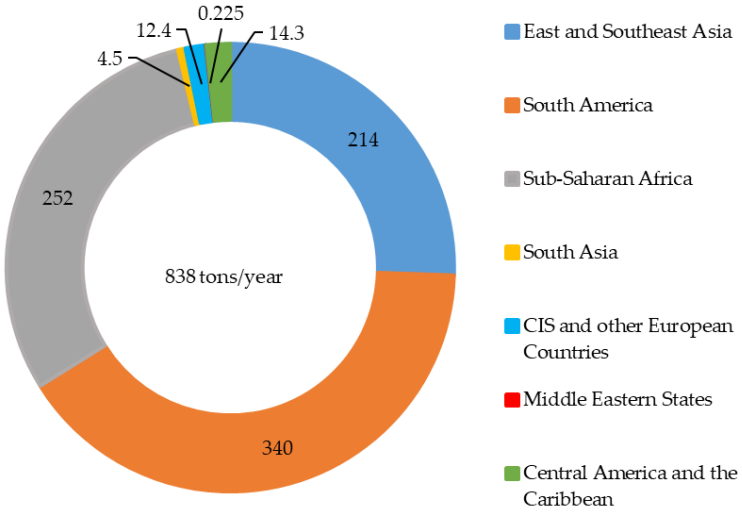

Figure 1.1. Regional results of global Hg emissions into air from the ASGM sources. Each value represents tons/year (UNEP, 2019).

as the primary sources (UNEP, 2019). Meanwhile, ASGM occurs in more than 70 nations worldwide, with an estimated 16 million miners who afford up to 20% of the annual global gold production (UNEP, 2019). According to the global inventory of the UNEP in 2015 (UNEP, 2019), 2220 tons of Hg was emitted to the atmosphere from all anthropogenic sources. Notably, 38% (838 tons) of Hg was emitted from the ASGM sources (Figure 1.1).

1.2. Hg Use in ASGM Communities

The use of Hg is quite common in ASGM sectors worldwide, including Southeast Asian countries such as Cambodia, Indonesia, Laos, Myanmar, the Philippines, and Thailand. The earliest records of Hg use in alchemy and amalgamation were from Egypt and China more than 3000 years ago (Hylander & Meili, 2003). Mercury has been used in inexpensive, easy, and rapid approaches for extracting gold from its ore and soil (UNEP, 2012). Notably, owing to weak legislation, poor engagement, contribution of artisanal

miners, and easily accessible of robust black market for Hg usage in the ASGM will continue to persist (Clifford, 2014; Hilson, 2006; Sousa et al., 2011).

Myanmar, a developing country in Southeast Asia, has various mineral and natural resources, such as for jade, gold, ruby, and copper. Myanmar has been facing overexploitation of natural resources for more than two decades because its people seek to extract its natural resources illegally (Htun, 2014). Additionally, 70% of the population of Myanmar is in rural areas and rely on natural resources. Meanwhile, gold production in Myanmar has increased slightly in recent years, reaching 1,700 kg in 2016 (McFarlane & Villalobos, 2019). ASGM activities in this country have been conducted throughout the states and regions of the country, namely, Bago, Kachin, Mandalay, Mon, Sagaing, Shan, and Tanintaryi (Figure 1.2) (Distribution of ASGM activities in Myanmar, 2018).

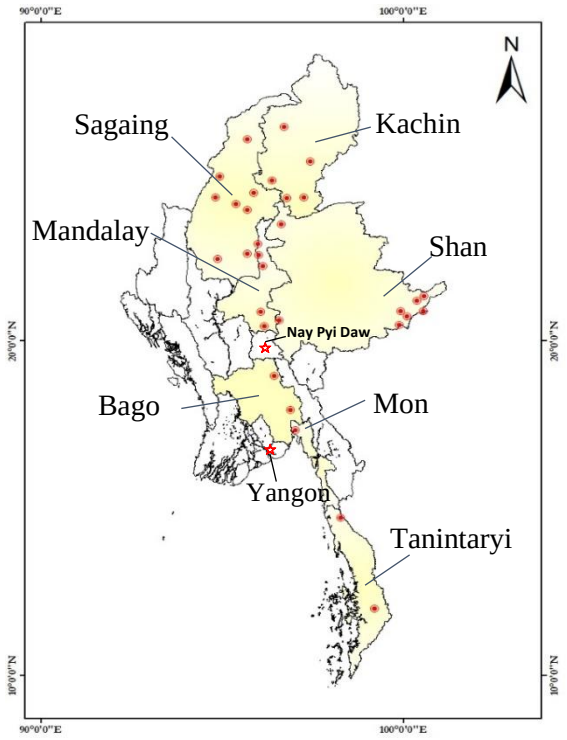

Figure 1.2. Distribution of artisanal and small-scale gold mining (ASGM) activities in the states and regions of Myanmar by township.

Various ASGM processes can be categorized on the basis of region and depend on the gold deposit types. ASGM can be classified using several methods such as panning, river mining with bucket dredges, suction dredging, and hydraulic mining. Alluvial deposits (river sediments) and hard-rock deposits (typically gold in quartz veins) have been exploited the gold ore by local and migrant miners. In the most common method for ASGM in Myanmar, gold ore is excavated via underground or open-pit mining, after which it is dried and ground using a powdering machine. The resulting powder is placed in a pan containing water to separate gold particles via gravity settling. Gold particles are collected at the bottom of the pan together with sand. A piece of Hg (like a finger-tip) is added to the pan to extract gold by forming a gold–Hg amalgam, which is squeezed by hand through a fabric cloth. Subsequently, a mine operator vaporizes the Hg in the gold-amalgam using a burner to obtain pure gold. Hg vapors are consequently released into the atmosphere and deposited into aquatic and terrestrial ecosystems. The ASGM practices in the considered study areas are summarized in Figures 1.3 and 1.4.

1.3. Minamata Convention on Hg

The Minamata Convention on Hg became one of the first worldwide environmental agreements in the 21st century. The convention was adopted in 2013, and to date, 123 countries have signed the agreement. The convention aims “to protect human health and the environment from anthropogenic emissions and releases of Hg and Hg compounds and it sets out a range of measures to meet the objective” (Parties et al., 2009). According to article 7 of the Minamata Convention, each party from an ASGM shall develop a national action plan regarding Annex C, which is indicating to implement national objectives and reduction targets and actions to eliminate the Hg and related

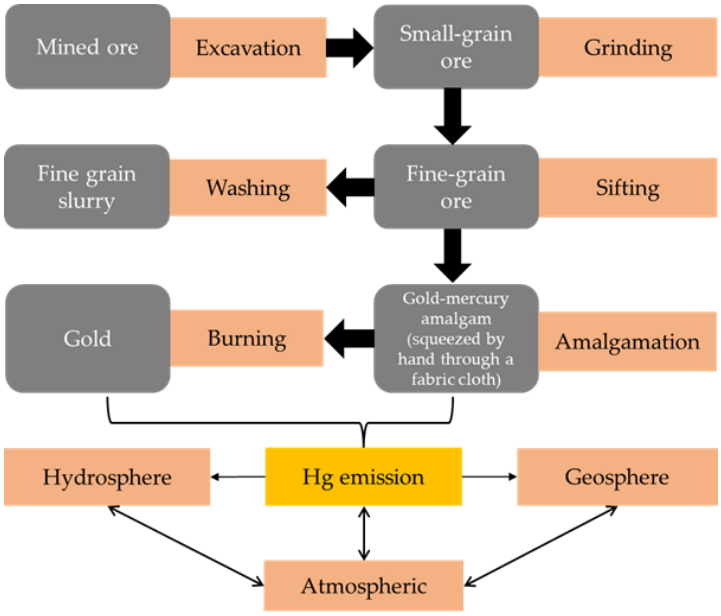

Figure 1.3. Flow chart showing general ASGM processes.

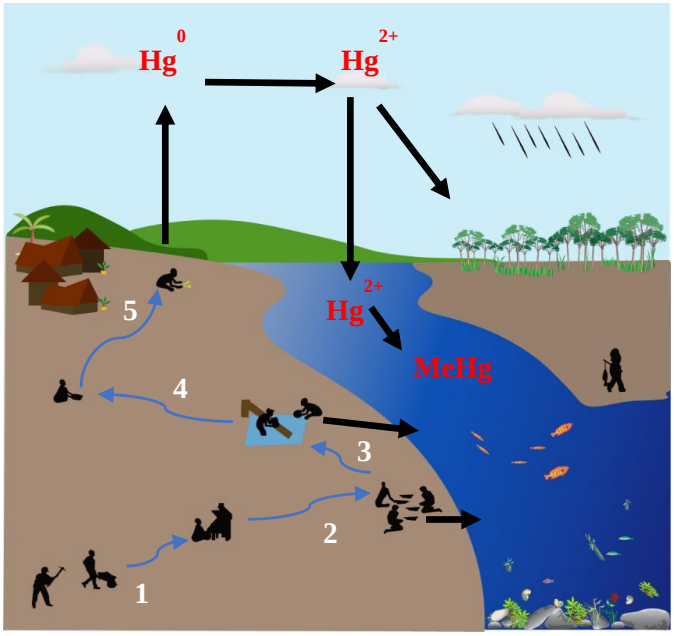

Figure 1.4. General ASGM processes involving (1) excavation, (2) grinding and sifting, (3) washing, (4) panning, and (5) gold-Hg-amalgam burning.

compounds. In the national action plan (NAP) for ASGM sectors, the informal ASGM sector must be regulated to accomplish the requirements for reducing the Hg in the country. Key to an NAP is the development of Hg inventories and baselines in the ASGM sector to monitor improvements and establish regulatory standards for Hg emission reduction. The pertinent parties must cooperate with the relevant stakeholders from governments, industry, NGOs, and academia. Subsequently, the parties need to build awareness regarding all Hg compounds in an ASGM process, promote non-Hg alternative practices, and provide technical and financial support.

The countries that have not have not ratified the Minamata Convention in the Association of Southeast Asian Nations (ASEAN), include Brunei, Laos, and Myanmar. However, in Myanmar, the NAP for Minamata Initial Assessment, which is funded by a global environmental facility, has started a national Hg inventory. The status of the Minamata Convention in ASEAN countries is summarized in Table 1.1.

1.4. Objective

Mercury pollution is a worldwide problem especially in ASGM countries. The number of artisanal miners has increased over the years and now totals to ~45 million people (Delve, 2022), with at least half of them engaged in gold mining, extracting up to 450 tons of gold per year in at least 70 countries (Seccatore et al., 2014). ASGM activities produce increasing amounts of gold from countries in Africa (e.g., Ghana, Mali, Sudan, Tanzania, and Zimbabwe), Latin America (e.g., Brazil, Colombia, and Peru), and Asia (e.g., China, Indonesia, Mongolia, Myanmar, and the Philippines).

This study emphasized Myanmar and other ASEAN countries that are practicing ASGM. Similar to other developing countries, environmental challenges in Myanmar

Table 1.1. Minamata Convention status in ASEAN countries (UNEP, 2022).

Participants	Signature Date	Status	Date (Ratification/ Accession/ Approval)
Indonesia	10/10/2013	Ratification	09/22/2017
The Philippines	10/10/2013	Ratification	8/7/2020
Cambodia	10/10/2013	Ratification	8/4/2021
Vietnam	11/10/2013	Approval	06/26/2017
Malaysia	24/09/2014	Signature	N.A.
Laos	N.A.	Accession	09/21/2017
Thailand	N.A.	Accession	06/22/2017
Brunei	N.A.	N.A.	N.A.
Myanmar	N.A.	N.A.	N.A.

N.A.; not available.

have been given strong consideration since natural resources have been extracted by illegal measures. Achieving an environmental balance has become a crucial role for such challenges. Unfortunately, Myanmar has insufficient professional labors with acquired skills; an ineffective governing mechanism; no transparency for trading by-products of gold, specifically Hg; and minimal research activities. Therefore, there are only six publications on Hg pollution in Myanmar up to now (Kawakami et al., 2019; Kuang et al., 2022; Kyaw et al., 2020; Osawa & Hatsukawa, 2015; Tun et al., 2020; Wongsasuluk et al., 2021).

This review has identified and assessed the critical Hg pollution issues in Myanmar and other Southeast Asian countries. This study outlines the Hg problems that are of crucial concern to the citizens of these nations. We evaluated the Hg contamination in

environmental media and the risks of Hg exposure on human health and propose a relevant policy framework regarding Hg issues.

2. Materials and Methods

2.1. Study Selection

The study identified the relevant literature published between 2000 and 2021 using databases including *PubMed, Web of Science, Springer, Science Direct,* and *Google Scholar*. The keywords used during the search were "Hg", "ASGM", "Myanmar", "Indonesia", "the Philippines", and "Malaysia". Research materials on international regulations, laws, and procedures related to Hg problems were also considered. The study

Table 1.2. Criteria for inclusion and exclusion of a study.

Inclusion	**Exclusion**
Studies related to ASGM communities	Studies in other industries, such as coal-fired power plant
Studies on Hg compounds, total Hg, inorganic Hg, and MeHg	Unrelated compounds, such as ethylmercury
Emphasis on Hg concentration in environmental media (e.g., air, water, and soil)	Measurement of Hg in other environmental media
Emphasis on Hg concentrations in biomonitors of plants, fish, and human hair	Measurement of Hg in other biological indicators
Reports relating to human-health risk assessment in ASGM communities	Reports relating to human-health risk assessment in other industries

focused on research articles from Myanmar and other ASEAN countries. To conduct the screening study, two reviewers (P.S.S. and T.A.) compared the titles and abstracts of the studies according to the inclusion and exclusion criteria presented in Table 1.2.

2.2. Quality Assessment

In selecting the literature, the study focused on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statements (Yepes-Nuñez et al., 2021) on identification, and screening, and included research as shown in Figure 5. The search method considered mainly published literature on Hg-related studies in environmental science, social science, and public health. The study focused on original research articles and systematic reviews. To ensure the quality of the evaluation, duplications were evaluated and checked rigorously. In the exclusion criteria, we

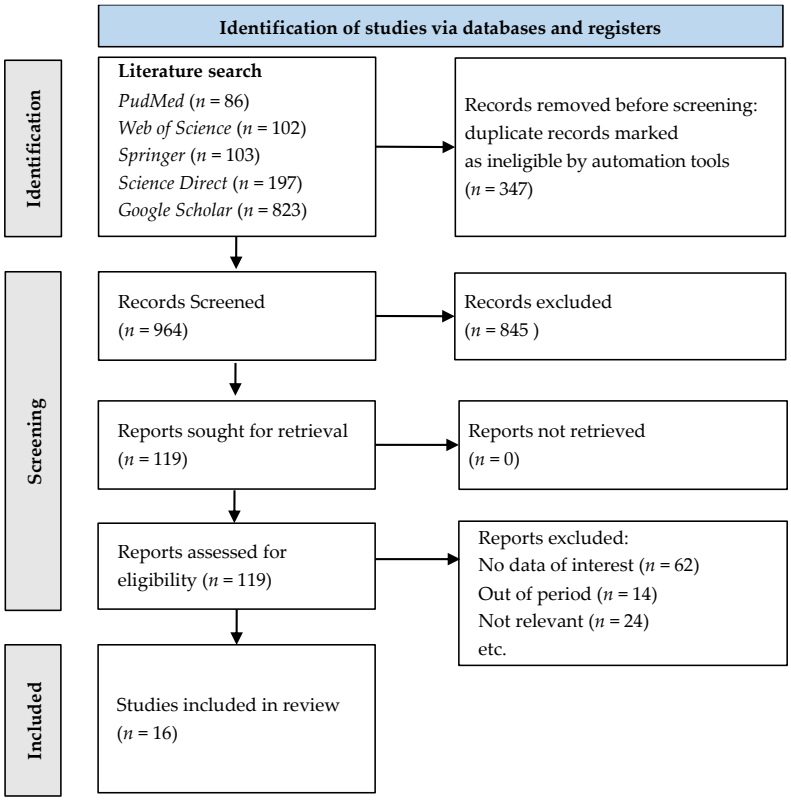

Figure 1.5. PRISMA flow diagram showing the search and selection process.

considered the publication year (2000–2021) the language used in the research articles. Only research published in English from the study areas in Southeast Asian countries were included. Third-party tools (e.g., Microsoft Excel and Mendeley) were used for importing website data and data screening.

3. Results

3.1. Hg Concentration in Air

Hg in the atmosphere occurs primarily in three forms, namely the gaseous state of elemental Hg (Hg(0)), reactive gaseous Hg (Hg(II)), and total particulate Hg (Hg(p)) (Munthe et al., 2001). Hg(0) emission from ASGM activities is the highest Hg emission source. Hg vapor, (mainly in the chemical form of elemental Hg(0)) can travel vast distances in the air and be deposited or captured in forest treetops and leaves (Crespo-Lopez et al., 2021). According to the 2018 global Hg assessment report, the global emission of Hg into the air in 2015 from ASGM sources was 838 tons, with East and Southeast Asian countries accounting for ~214 tons (UNEP, 2019). Recent studies have showed very high Hg concentrations in the atmosphere resulting from ASGM activities in Central Sulawesi, Indonesia (Nakazawa et al., 2016), Camarines Norte, the Philippines (Murao et al., 2021), and Mandalay region, Myanmar (Kawakami et al., 2019). The Hg concentrations in air from ASGM activities in Indonesia, Myanmar, and the Philippines are summarized in Table 1.3.

In Central Sulawesi, Indonesia, the highest average concentrations of 24 h ambient Hg (0) of 9,172 ng/m^3 were found in the gold-processing areas that refined gold (including the stages of Hg amalgam burning) (Nakazawa et al., 2016). This total value was nine times higher than the WHO guideline limit of 1,000 ng/m^3 (WHO, 2000).

Table 1.3. Summary of Hg concentration in air from Indonesia, Myanmar, and the Philippines.

Location(s)	Sample sources	*n*	Hg concentration (ng/m^3)	Reference
Palu city, Sulawesi, Indonesia	Gold-processing area		9,172 ± 16,422 (mean ± SD)	Nakazawa et al., 2016
	Northern area of city		514 ± 420 (mean ± SD)	
	Central area of city	21	141 ± 141 (mean ± SD)	
	Western area of city		22 ± 15 (mean ± SD)	
	Southern area of city		116 ± 135 (mean ± SD)	
Mandalay region, Myanmar	ASGM site	13	0–10,900	Kawakami et al., 2019
		19	0.66–74,000	
Province of Camarines Norte, The Philippines	ASGM site	4	7.8–314,000	Murao et al., 2021

N.A.; not available, S.D.; standard deviation.

Further, this study also considered indoor and outdoor air Hg (0) concentration in the Palu city area and the village of Mangkahui. The highest indoor and outdoor air concentrations of Hg (0) in the Palu city were 450 and 2,250 ng/m^3, respectively. In the village of Mangkahui, the Hg (0) concentrations in the indoor and outdoor air were 196 and 103

ng/m^3, respectively, at site A. Meanwhile, the values were 238 and 279 ng/m^3, respectively, at site B.

A study investigated the atmospheric Hg concentration at an ASGM site in the Mandalay region of central Myanmar via two surveys (Kawakami et al., 2019). In the first and second survey, the highest Hg concentrations of 10,900 and 74,000 ng/m^3, respectively, were noted in an amalgamation-burning area of an ASGM site. These values were several times higher than the Hg limit value in the WHO guidelines (WHO, 2000). In addition, the study suggested that Hg was dispersed not only in the ASGM areas but also in nearby residential areas.

Atmospheric Hg pollution has been identified in the Province of Camarines Norte, the Philippines, by Murao et al. (Murao et al., 2021. The authors focused on an area of a rod-mill station in the ASGM that recently burned gold amalgamation. The highest Hg concentration in air was 314,000 ng/m^3, which was considerably higher than WHO guideline (1,000 ng/m^3) (WHO, 2000) at the rod-mill station in Benit, the Philippines. Meanwhile, the lowest concentration was 7.8 ng/m^3 at the same place 4 weeks after the burning.

In comparison with other air constituents, gaseous Hg (0) is relatively inert. Hg (0) from both anthropogenic and natural emissions can be transported over large distances by air and stay in the atmosphere for a year; therefore, Hg (0) can deposit in terrestrial and aquatic ecosystems (Schroeder, 1998). The studies from Indonesia, Myanmar, and the Philippines have revealed that the atmospheric concentration of Hg were much higher in the ASGM areas that burn gold amalgamation. The concentrations were also higher than the WHO guidelines (WHO, 2000). Therefore, a Hg recovery method should be considered in the ASGM industries.

3.2. Hg Concentration in Water Bodies

Water resources can be impacted by various ASGM operation steps, such as mined-ore sifting and washing. An amalgamation process used in ASGM sectors typically discharges wastewater into water bodies. Subsequently, aquatic organisms are exposed to elevated Hg levels. Furthermore, inorganic Hg can be transformed into toxic MeHg (Pataranawat et al., 2007). MeHg in aquatic organisms is biomagnified through the food chain. Notably, fish intake is the primary source of Hg exposure in humans (Berzas Nevado et al., 2003). Mercury concentrations in waterbodies of Indonesia, Malaysia, Myanmar, the Philippines, and Thailand are presented in Figure 1.6.

A study in the Cikaniki River, Bogor, Indonesia, reported Hg concentrations in the river water ranging from 0.4 to 9.4 µg/L. The highest concentrations were found near an ASGM village. In this study, significant correlations were observed between Hg (0)

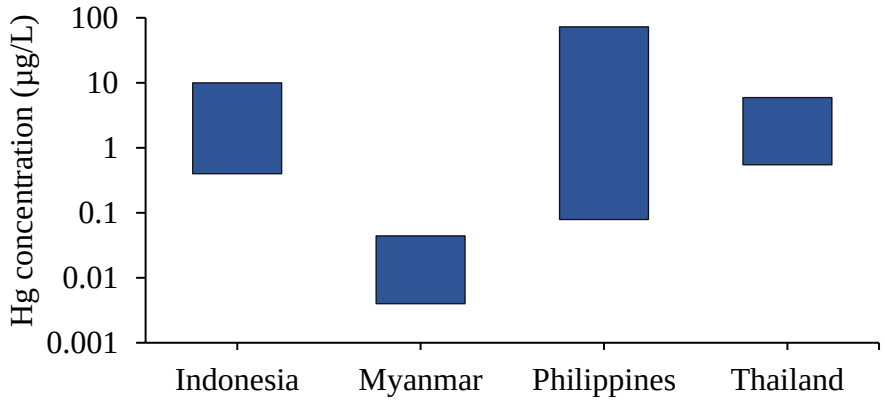

Figure 1.6. Hg concentration in waterbodies from Indonesia (Tomiyasu et al., 2017), Myanmar (Kawakami et al., 2019), the Philippines (Akagi et al., 2000), and Thailand (Pataranawat et al., 2007). Each piece of data represents a Hg concentration of range value, which was from a single study.

and MeHg since MeHg concentration was considerably lower than Hg(0). The fact assumes that mining wastes was not a direct source of MeHg in the Cikaniki River (Tomiyasu et al., 2017). Otherwise, Hg(0) deposited in river water can be subjected to methylation, suggesting that the change in chemical forms of Hg in water systems should be conducted in the future. An earlier study of the river conducted in 2009 reported Hg concentrations of 0.09–9.1 μg/L (Tomiyasu et al., 2013) and showed similar results, indicating the continuous pollution of the Cikanaki River.

In a study conducted in the Mandalay region, Myanmar, two groundwater samples were collected from five ASGM areas (Kawakami et al., 2019). Irrawaddy River is one of the main rivers in Myanmar, which is located near an ASGM area. Surface water samples from upstream and downstream areas of this river were collected. Hg concentrations were also determined in groundwater at the nearby residential areas. The Hg concentrations in the sampled groundwater were in the range of 0–0.04 μg/L. The area closest to gold-mining activities typically showed Hg contamination (Elvince et al., 2008). The samples obtained in the Irrawaddy River, which was downstream from the ASGM area, showed a Hg concentration of 0.005 μg/L Hg, and samples taken from the upper stream of the river contained 0.004 μg/L of Hg. The reported Hg concentrations in the Irrawaddy river were slightly higher than the typical concentrations of Hg in lakes and rivers (0.001–0.003) (World Bank, 1998) but not exceptional.

Interestingly, the Hijo River in the Philippines supports food security and is a means of living for local people who participate in it for gold processing. Wastewater containing Hg and cyanide from mine tailings is discharged into the river without treatment (Akagi et al., 2000). Additionally, the Naboc River in the Philippines receives effluent water from mining operations. The Hg concentration found in the Hijo, Naboc, and Kingking Rivers

were 78.4, 72.8, and 75.2 µg/L, respectively (Akagi et al., 2000). These levels are much higher than the national standard limit (i.e., 1 µg/L) of the Philippines (DENR, 2016).

A study in Phichit Province, Thailand, focused on the surface water of the Klong Dai Nam Khun and Klong Sa Luang canals, which were connected with a mining area (Pataranawat et al., 2007). Thirteen locations with aquatic habitats, including upstream, downstream, reservoir, and other water bodies near a gold-processing area and separatory ditch that were used for gold-ore separation processes, were considered. The study emphasized evaluation of the Hg concentrations level-related Hg-contaminated sites and their distances from ASGM sites, showing Hg concentrations in the range of 0.6–5.4 µg/L. The workplace area showed a higher Hg concentration than areas at greater distances upstream and downstream because the amalgam processes were conducted near the sampling locations.

In the considered studies, the studied samples from Indonesia (Tomiyasu et al., 2017), the Philippines (Akagi et al., 2000), and Thailand (Pataranawat et al., 2007) exceeded WHO guideline limit of 0.5 µg/L of Hg (Kawakami et al., 2019). ASGM areas could affect Hg concentrations in surface water because Hg can be derived from atmospheric sources (Vandal et al., 1991). Further, Hg can transfer to the food chain in aquatic environments. Therefore, the effluent from improperly treated wastewater can be detrimental to marine life and people who consume seafood.

3.3. Hg Concentration in Soil

Soil is a key indicator for monitoring environmental Hg concentration because Hg entering the atmosphere from amalgamation burning can deposit in the top layers of soil. It is necessary to understand the level of Hg concentration to prevent Hg pollution of soil.

For the topsoil profile, Hg concentrations have been found to decline from the topsoil to the deeper horizon (Santos-Francés et al., 2011; Wang et al., 2016). In addition, Hg sorption from the air may contribute to Hg accumulation in topsoil horizons through litter accumulation and decomposition. The sources of Hg contamination of soil are fertilizers, lime, sludges, and manures (Azevedo & Rodriguez, 2012). A summary of the Hg levels in soils from ASGM sites in Indonesia, Myanmar, the Philippines, and Thailand is shown in Figure 1.7.

An Indonesian study classified forest and paddy field soils impacted by ASGM activities (Tomiyasu et al., 2017). The Hg concentration analyzed in forest soil and paddy field soils were 0.07–16.7 and 0.4–24.9 μg/g, respectively. Additionally, the concentrations of MeHg were in the range of 0.07–2 μg/kg in forest soils and 0.07-56.3 μg/kg in paddy field soils. These data demonstrated that paddy field soil is particularly affected by ASGM activities (Tomiyasu et al., 2017).

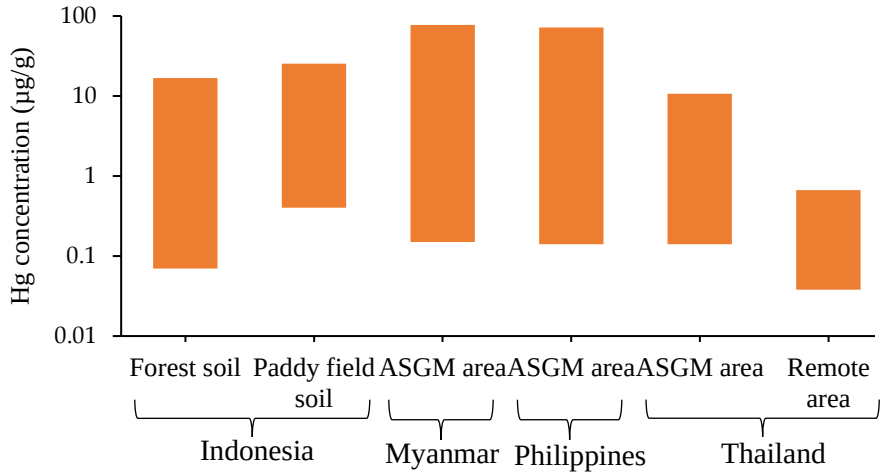

Figure 1.7. Hg concentration in soil from Indonesia (Tomiyasu et al., 2019), Myanmar (Tun et al., 2021), Thailand (Pataranawat et al., 2007), and the Philippines (Murao et al., 2021). Each piece of data represents the Hg concentration of range value, which was from a single study.

ASGM activities are widely performed in the upper part of Banmauk Township, Sagaing Region, Myanmar. A study investigated soil samples from the placer gold-deposition area and identified soil matrices based on ASGM operation processes, such as ore processing, sluicing, panning, and amalgamation (Tun et al., 2020). The soil matrix from the amalgamation process exhibited the highest Hg concentration of 77.44 μg/g, whereas Hg concentrations during soil ore processing, sluicing, and panning stages (gold-amalgamation stage) were 0.68, 0.51, and 4.86 μg/g, respectively (Tun et al., 2020).

A study conducted in the Philippines determined Hg concentration in soils obtained from potentially contaminated hotspots and the areas distant from such spots. The highest Hg concentration observed was 71.75 μg/g in the sample from a rod-mill station in the amalgamation-burning workplace. By contrast, the lowest concentration observed was 0.15 μg/g in the sample from a non-mining area, showing that the higher Hg concentration had contaminated the vicinity of the ASGM area (Murao et al., 2021).

A study of an ASGM operation in the Phichit region, Thailand, considered surface soil (0–5 cm depth) from mining and remote areas. The Hg concentrations in the mining and remote areas were in the range of 0.14 – 10.56 and 0.038 – 0.632 μg/g, respectively. The higher Hg concentration observed in the mining area indicated that Hg vapor emitted into the atmosphere was likely deposited on soil surfaces near the burning stoves. This was because of the 7.8 h/day amalgamation process takes place for extraction of 60–150 g of gold (Pataranawat et al., 2007).

A study reported that Hg concentrations in soil do not typically exceed 0.1 μg/g, and normal levels in soil were reported. Moreover, the normal Hg levels in soil were 0.05–0.08 μg/g (World Bank, 1998). The data from Myanmar, the Philippines, and Thailand showed higher Hg levels than United States Environmental Protection Agency (US EPA)

generic soil guidelines value (0-0.2 μg/g) (Murphy et al., 2008). The study found that amalgamation process in ASGM areas contributed considerably to the Hg concentrations found. Therefore, people residing near the ASGM area could be impacted by Hg exposure during the amalgamation process.

3.4. Hg Concentration in Plants

Plants are widely used as biomonitors for monitoring environmental Hg (Lodenius, 2013). Rasmussen et al. found that among vegetative structures, the leaves contained the highest Hg concentrations (Rasmussen et al., 1991). In plants that absorb Hg primarily from the soil, Hg contents were found to be higher in the roots. Conversely, for the plants that adsorb Hg primarily from the air, Hg contents were found to be higher in the shoots and leaf tissues (R. Li et al., 2017). Some studies have reported that crops such as vegetables are the sources of Hg exposure for people living in Hg-mining areas (H. Zhang et al., 2010). The Hg contents found in plant samples from Indonesia, Myanmar, the Philippines, and Thailand are presented in Figure 1.8.

Some recent studies from Indonesia have reported high Hg concentrations of 1.4 μg/g dry weight (d.w.) in leaves from plants that grew near ASGM locations (Mahmud et al., 2019). Similarly, contaminated forage plants (an edible animal feedstock) were found at a gold-mining site in Southeast Sulawesi Province, Indonesia (Basri et al., 2020). Fresh forage plant samples from the Rarowatu and North Rarowatu Districts of Bombana were studied (Basri et al., 2020). The sampling locations were divided into reference, mining

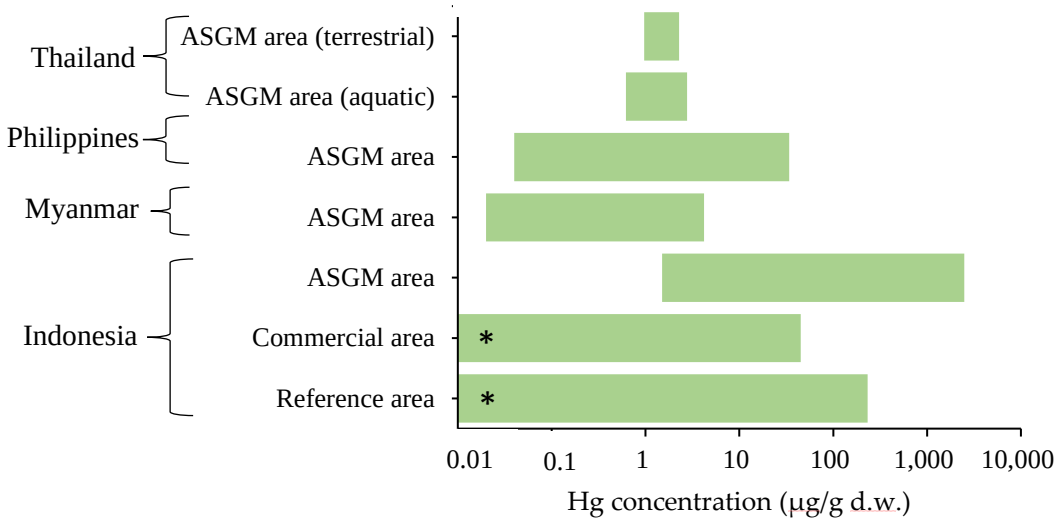

Figure 1.8. Hg concentration in plants from Indonesia (Basri et al., 2020), Myanmar (Kuang et al., 2022), the Philippines (Murao et al., n.d.), and Thailand (Pataranawat et al., 2007). Each datum represents Hg concentration of range value, which was from a single study. *. Minimum value of "0".

commercial, and ASGM. The highest Hg content of 9.9 ± 14 μg/g d.w. was found in the ASGM area. The values in the commercial mining and reference areas were 3.20 ± 3.50 and 2.70 ± 2.80 μg/g d.w., respectively. According to the critical limits for Hg related to ecotoxicological effects on plants, the Hg levels in forage plants can be divided into three categories: high (>3 μg/g), low–moderate (0.1–3.0 μg/g), and low (0.1 μg/g) (Basri et al., 2020).

A study from the Mandalay Region, Myanmar, included a preliminary survey that assessed the Hg air pollution in advance of future studies by examining tree bark, leaves, and blades of grass from *Typha latifolia* L. (leaf) species, *Azadirachta indica* (bark), *Terminalia catappa* L. (bark) *Manifera indica* L. (leaf), and *Naringi crenulata* (Thanaka (leaf)) (Kuang et al., 2022). Hg from the atmosphere and the soil can be deposited in plants (Browne & Fang, 1978). The highest Hg concentration found was 4.17 μg/g d.w.

in a Thanaka leaf near a gold shop, whereas the lowest concentration found was 0.02 μg/g d.w. in *Typha latifolia* L. leaf sample obtained some distance away from ASGM areas. The highest Hg concentrations found were in samples obtained near the gold refinery area.

Plants can serve as an indicator to regulate the uptake and transport of pollutants to the air because their internal pollutant concentrations are generally identical to the pollutant concentrations detected in the parent soil (Peralta-Videa et al., 2009). A study from the Philippines considered Hg concentrations in plant species including *Dadvalia* sp., *Alugbatging puti*, *Citrus* sp., Cacao, *Dilang aso* (Murao et al., 2021). The study analyzed plant samples from an ASGM area and a few meters away from it. The Hg concentration in plants ranged between 0.04 and 34 μg/g. The highest Hg concentrations was found in *Dadvalia*, which grew near a rod-mill station in the ASGM area (Murao et al., 2021).

In a study from Thailand, neem leaves and flowers from aquatic and terrestrial environments in the ASGM workplace in Phichit Province was investigated (Pataranawat et al., 2007). Neem flowers from aquatic sites showed Hg levels of 0.62–2.151 μg/g d.w. (Pataranawat et al., 2007). Similarly, Neem leaves from terrestrial sites exhibited Hg levels in the range of 0.967 and 1.30 μg/g d.w.. The Neem flowers were purposely collected from the aquatic tract, and the results showed that the highest Hg concentrations was found near the Hg emission source. Further, the study suggested that Hg concentration in Neem flowers growing along the aquatic sampling site was related to the concentration of Hg in sediment at the same location (Pataranawat et al., 2007). The Hg levels were higher than the maximum permissible limit of Hg content (0.5 μg/g w.w.) for biota tissue (Sommar et al., 2020). Moreover, a study highlighted that the concentration of Hg can be deposited in legume species such as *Indigofera enneaphylla* and *Desmodium*

triflorum (Murao et al., 2021). Therefore, the study suggested avoiding eating the plants near potentially Hg-contaminated areas.

Plants obtained in Indonesia, Myanmar, the Philippines, and Thailand have been found to contain Hg concentrations that were above the FAO/WHO guideline values (0.5 μg/g w.w.) (Rajaee et al., 2015, WHO, 2013).

3.5. Hg Concentration in Fish

Fish consumption is one of the most important factors contributing to Hg uptake in humans. Hg concentrations in fish tissues can be affected by the age, length, and weight of the fish (Castilhos et al., 2006). Freshwater biota accumulate Hg from both natural and anthropogenic sources. Most fish have natural Hg levels of 0.02–0.3 μg/g wet weight (w.w.); however, small, and short-lived herbivorous fish species have been found with a Hg level of 0.01 μg/g w.w. (Suckcharoen et al., 1978). According to the recommendation of the FAO/WHO, the Hg content in a fish should not be more than 0.5 μg/g w.w. (FAO & WHO et al., 2015). Hg concenteation in fish from Indonesia and the Philippines based on w.w. area presented in Figure 1.9.

A study in Cambodia-involved the collection of 82 fish species from local fishermen/fisherwomen in Kampi pool near Kraite, which is located near the O Tron gold mining area (Murphy et al., 2008). The Hg concentration in the collected fish samples (n = 160) ranged between 0.008 and 0.64 μg/g. Additionally, the study grouped the size of fish as “small size” and “big size.” The big size fish showed an average Hg content of 0.128 μg/g, which was considerably higher than the average Hg of 0.086 μg/g in the small-size fish (Murphy et al., 2008). According to Baran et al. (Baran E., 2007), Cambodians consume an average of 1.26 kg of fish each week; thus, Cambodians

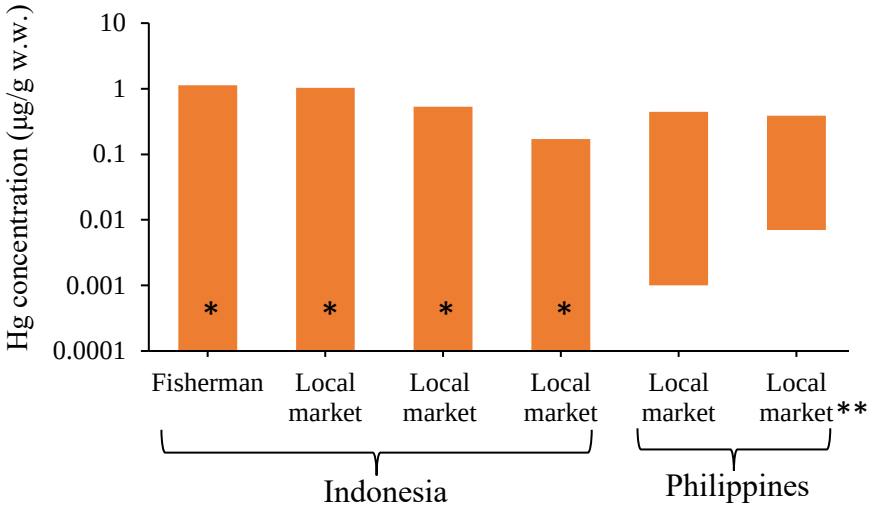

Figure 1.9. Hg concentrations in fish from Indonesia (Bentley & Soebandrio, 2017), and the Philippines (Akagi et al., 2000). Each datum represents Hg concentration of range value, which was from a single study. *; minimum value of "0", **; MeHg concentration

who consume more fish than the normal quantity intake higher Hg levels and are at a higher health risk (Murphy et al., 2008).

Recent studies from Indonesia conducted fish sampling during 2007 to 2011 in Ratatotok Subdistrict, North Sulawesi, Indonesia, which was near the Mesel gold mining area (Bentley & Soebandrio, 2017). Local people from the studied area, which has an active fishing economy, have faced health issues during the period of active mining. The study involved the collection of fish samples from fishermen/fisherwomen and local market (Bentley & Soebandrio, 2017). The fish samples from a Buyat Pantai fisherman showed Hg levels of 0.00–1.13 μg/g (w.w.) The samples from Buyat, Ratatotok, and Manado fish markets showed levels of 0.00–1.03, 0.00–0.53, and 0.00–0.17 μg/g (w.w.), respectively (Bentley & Soebandrio, 2017). Thus, except for the Manado fish market, the fish samples from other sources exceeded the WHO standard guideline (FAO & WHO,

2015). Nonetheless, the reported mean Hg concentrations in fish were within the standard limit for consumption.

Surveys were conducted to determine Hg concentration in marine samples in Davao del Norte, south of Manila, the Philippines, and near a gold processing area. At the local market of Apokon, Tagum, seventeen specimens of fish and one seaweed sample were examined to determine the Hg and MeHg concentrations, which ranged between 0.001 and 0.44 μg/g, and 0.007 and 0.38 μg/g w.w., respectively (Akagi et al., 2000).

The considered studies revealed that the maximum concentration of Hg found in fish from Cambodia, Indonesia, and the Philippines were 1.13 μg/g, 0.44 μg/g w.w., and 0.64 μg/g w.w., respectively. Compared with the studies from Latin America such Brazil (1.04–2.84 μg/g w.w.), Colombia (1.60–4.50 μg/g w.w.), Bolivia (1.08–2.86 μg/g w.w.), and Ecuador (1.39–1.6 μg/g w.w.) (Canham et al., 2021), the reported Hg concentrations in Southeast Asia were relatively lower.

3.6. Hg Concentration in Human Hair

Hair is a common biomarker for characterizing MeHg exposures (UNEP and WHO, 2008). Low Hg concentrations have been considered risks for neurosis (50 μg/g) and health issues (11 μg/g) in unborns (Vu Duc Loi et al., 2006). Moreover, a low Hg level in hair has also been associated with a low susceptibility of hair for Hg vapor. Hg concentrations measured in human hair from Cambodia, Indonesia, Myanmar, the Philippines, and Thailand are summarized in Table 1.4.

A study in Cambodia study involved the collection of human hair samples around the Mekong River, which is one of the world's major rivers (Murphy et al., 2008). Hair samples were taken from people including mine workers living in the area of the O Tron

Table 1.4. Summary of Hg concentration in human hair from Cambodia, Indonesia, Myanmar, the Philippines, and Thailand.

Location	Sample source	Number of samples	Hg concentration (µg/g)	MeHg concentration (µg/g)	Reference
Mekong River, Cambodia (near O Tron gold mine)	Tonle Srepok	25	4.54*	N.A.	Murphy et al., 2008
	Tonle Kong	17	4.22*		
	Mekong N. Stung Treng	16	3.36*		
	Mekong Kratie	20	3.47*		
	All Males	32	5.21*		
	All Females	46	3.08*		
	All Adults	59	4.01*		
	All children (aged <13 yr)	19	3.38*		
	Women Ratanakirri	23	3.47*		

Location	Sample source	Number of samples	Hg concentration (μg/g)	MeHg concentration (μg/g)	Reference
	(mine impacted)				
	Women Mekong	23	2.7*		
Lebaksitu, Lebak regency, Java Island, Indonesia	ASGM area	41	0.847–9.015	0.37–4.33	Novirsa et al., 2022
Mandalay Region, Myanmar	ASGM area (miners and nonminers)	50	0.4–5.7 μg/g	N.A.	Kawakami et al., 2019
Acupan region, Benguet, the Philippines	ASGM area	70	0–26.6 μg/g	N.A.	Clemente et al., 2004
Nong Pra subdistrict,	Gold Miner	79	1.17 ± 0.05 (mean ± SD)	N.A.	Umbangtalad et al., 2007

Location	Sample source	Number of samples	Hg concentration (μg/g)	MeHg concentration (μg/g)	Reference
Wang Sai Poon district, Phichit Province, Thailand	School Children	59	0.93 ± 0.01 (mean ± SD)		

N.A.; not analyzed, S.D; standard deviation, *; mean concentration.

gold mines and upstream and downstream along the Mekong River. These results revealed that the mean Hg concentration (5.21 μg/g) in the hair samples from men (*n* = 32) was higher than that of women (3.08 μg/g) (*n* = 46). When the female hair samples were sorted by sample area, the women from Ratanakiri province, near mine-affected areas had a substantially higher Hg concentration of (3.47 μg/g) (*n* = 23), than a control group (2.7 μg/g) (*n* = 23) (Murphy et al., 2008). Hg levels in the Cambodian hair sample exceeded those observed near gold mines in the Philippines, where association of impaired human health with Hg concentration was observed (Akagi et al., 2000).

A study involved the collection of human hair samples from an active ASGM area operating for more than 20 years in Lebaksitu, Indonesia (Novirsa et al., 2020). The Hg hotspot village (Lebak-1) and downstream village (Lebak-2) were considered as high- and low-risk areas, respectively. Human hair samples from both villages showed a mean Hg content of 3.2 μg/g, with a range of 0.847 to 9.015 μg/g (Novirsa et al., 2020). The samples from Lebak-1 residents showed a considerably higher mean MeHg value

(2.12 μg/g) than other residents, indicating that Lebak-1 residents were more exposed to Hg than Lebak-2 residents. After comparison with other research on Hg-affected areas in Colombia (Salazar-Camacho et al., 2017), MeHg accumulation in hair from Indonesia was primarily caused due to consumption of food, such as fish and rice (Novirsa et al., n.d.).

In the Mandalay Region of Myanmar, human hair surveys were conducted of miners and nonminers living around the ASGM areas. The maximum Hg concentration in the hair samples of miners and nonminers were 5.7 and 2.9 μg/g, respectively (Kawakami et al., 2019a). The fact indicates that Hg concentration in human hair from the considered study was not at a level that would adversely affect human health because the approximate lowest levels of Hg that can cause neurosis and health problems in unborn fetuses are 50 and 11 μg/g, respectively (National Institute for Minamata Disease, Ministry of Environment, 2013; Salazar-Camacho et al., 2017).

Human hair samples from 70 inhabitants of Acupan, Benguet, in the northern regions of the Philippines were obtained (Clemente et al., 2004). In the large studied ASGM community, the age of the participants was in the range of 8 – 66 years. The results showed that the average Hg content in the inhabitants was 3.47 μg/g. Hg concentrations in nine interviewees were higher than the human biomonitor limit of 5 μg/g (Clemente et al., 2004). Additionally, the highest Hg concentration was 26.6 μg/g, which was found in a 46-year-old male participant who was involved actively in amalgamation burning and lived only 5 m away from the ASGM location.

Hair samples were obtained from miners, schoolchildren, and a control group from the Phanom Pha gold mining area located in Nong Pra subdistrict, Wang Sai Poon District, Phichit Province, Thailand (Umbangtalad et al., 2007). The study considered the miners

involved in the amalgamation process and working the ore preparation area as groups I and II, respecitvely. The schoolchildren, belonged to the group involved in gold mining activities The hair samples from miners showed an average Hg concentration of 1.17 (μg/g), which was within the reference group's Hg concentration range (Umbangtalad et al., 2007). The average Hg content in hair samples from schoolchildren in Group I and II were 0.95 μg/g and 0.90 μg/g, respectively. Both schoolchildren groups showed Hg concentrations that were within the range of the control (Umbangtalad et al., 2007). The fact suggests that lower Hg concentrations are expected in the hair because exposure to Hg is primarily due to inorganic Hg (i.e., Hg vapor) (Umbangtalad et al., 2007).

3.7. Health Risk Assessment of ASGM communities

A study in Central Sulawesi, Indonesia, examined the health risks Hg exposure caused by the Poboya ASGM sites at the residential areas of Palu city (Nakazawa et al., 2016). The study focused on miners and other residents to estimate their health risk exposure. In each of the five locations studied, the frequencies of each hazard quotient (HQ) ratio (HQ ratio ≥ 1) from gaseous Hg (0) inhalation risk were determined (Nakazawa et al., 2016). Based on daytime Hg (0) concentrations, only the 1.5% in the gold processing area showed HQ ratios of <1, suggesting no risk. However, 93% of the sample population was found to be at risk. There are high chances of inhaling Hg released via ASGM activities in studied area. The human health risk from Hg exposure is particularly high in the Poboya gold processing area and the areas close to Palu city. Moreover, 93% of the sample population in the Poboya area exceeded the no risk values with HQ ratio > 1. These findings suggest that people who work in the gold processing industry and nonminers in Palu city are at risk of adverse health impacts due to inhalation of Hg vapor.

A preliminary health survey conducted in ASGM area of Thabeikkyhin Township, Mandalay Region, Myanmar, involved the health inspection of men (*n* = 18) and women (*n* = 11) (Kyaw et al., 2020) to determine the health of the neurological system and respiratory functions. Based on the neurological assessment, three female miners who participated in ASGM panning and amalgamation processes for more than 5 years were diagnosed with mild tremors and ataxia. The respiratory assessment by spirometry on miners showed 38.9% normal, 27.8% mild, 27.8% moderate, and 5.6 % severe conditions. Meanwhile, the nonminer group exhibited 27.3% normal, 27.3% mild, and 45.5% moderate influence conditions (Kyaw et al., 2020). Furthermore, the study found that with an increased duration of mining activities, the FEC and FEV1 values declined, indicating a chronic damage of the respiratory function in the enrolled miners. Therefore, health inspections of the ASGM community in Myanmar should be conducted intensively.

The health impacts of Hg on miners and children in the vicinity of ASGM mining in Apokon, Tagum, Davao del Norte, the Philippines were studied (Akagi et al., 2000). The neurological effects found were were mainly located on the cranial nerves (17.1%), reflexes (5.1%), sensory (5.1%), cerebellar (3.89%), and motor nerves (1.2%). The neurological effects were characterized as follows: cranial nerve VIII abnormalities (6.87%), distally decreased vibratory sense (2.69%), palmomental reflex deficiency (2.4%), cranial nerve I (2.40%), visual acuity (2.10%), and Babinski (1.50%). Based on physical examination, abnormalities were found in all 163 children enrolled in the study with the following five predominant abnormalities: below average height, gingival discoloration, below average weight, adenopathy, and dermatologic irregularities

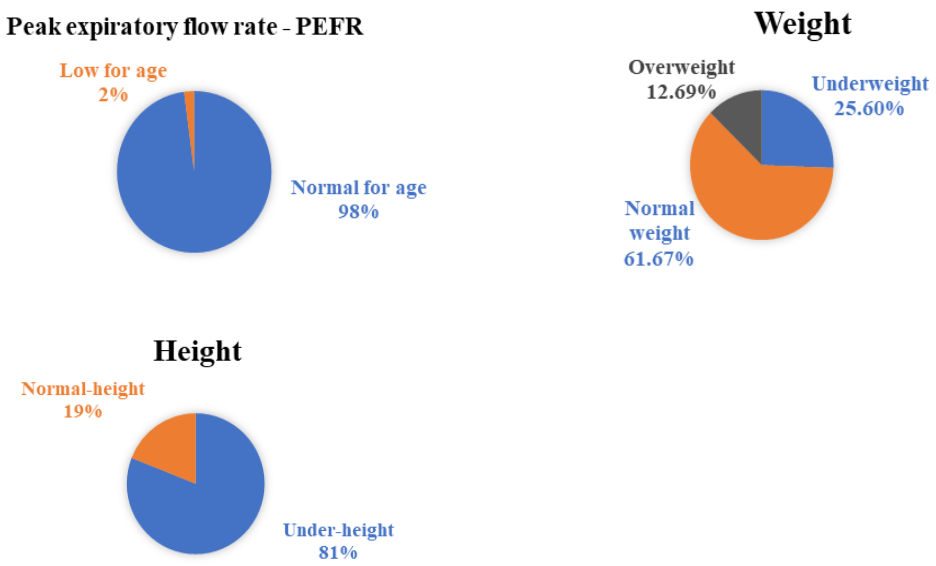

Figure 1.10. Predominant abnormalities found in schoolchildren of Apokon, Tagum, Davao del Norte, the Philippines (Akagi et al., 2000).

A study was conducted in the Phanom Pha gold mining area of Thailand (Umbangtalad et al., 2007). Two groups of miners and schoolchildren were divided into groups I (involvement in mining activities) and II (no involvement in mining activities) to estimate individual health risks. According to the U.S. EPA, the reference dosage is 0.0003 mg/kg/day (USEPA, 1999) and the HQ ratio represents the estimated exposure intake. Low exposure to Hg vapor in the group of miners was evidenced by the range of Hg in the air of 0.005–0.021 mg/m^3. The HQ ratios of group II indicated no risk (Umbangtalad et al., 2007). However, the HQ ratios ranged from 16 to 218 in group I, which were much higher than in the HQ values of group II. Regarding the group of schoolchildren, group I exhibited a low HQ value of 0.02 – 0.23 while group II showed an even lower HQ value of 0.01–0.02 (Umbangtalad et al., 2007). The higher HQ values of group I could be attributed to the Hg exposure from gold mining in the vicinity of amalgamation open burning. This suggests that the miners who work in the amalgamation

process are at the greatest risk of inhaling Hg vapor. Mitigation strategies to lower Hg contamination in the workplace must be considered.

4. Discussion

This paper reviewed the Hg pollution from ASGM areas in Myanmar and other Southeast Asian countries. Environmental indicators (e.g., air, water, and soil) and biomonitors (e.g., plants, fish, and human hair) were used in the considered studies. The concentrations of Hg in the air found at various areas in Indonesia, Myanmar, and the Philippines were higher than the standard limit values indicated in WHO guidelines (WHO, 2000). The high Hg concentrations in the air were mainly due to the burning of gold-amalgamation in the studies areas. By contrast, the reported concentrations of Hg in the air around ASGM areas in Idrija, Slovenia (<10 ng/m^3) (Kobal et al., 2017), and Guizhou, China (17.8 ng m^3) (Wang et al., 2007), were low. Moreover, in Almadén, Spain, where cinnabar was melted to produce Hg, the Hg levels reported were in the range of 100–14,000 ng/m^3 (Higueras et al., 2006), which were lower than the Hg levels in the ASGM areas in Myanmar and the Philippines.

In ASGM areas, water is essential for drinking and the domestic purposes of local people. Additionally, water purification is critical in the ASGM area because mine wastewater can be discharged directly into water bodies. Thus, the reviewed studies considered Hg concentrations in river water and groundwater around the ASGM areas. Hg concentrations in the water samples from Indonesia, the Philippines, and Thailand exceeded the WHO standard (0.5 µg/L) (WHO, 2017). Hg concentration in water samples from Myanmar was relatively lower compared with those from Indonesia, the Philippines, and Thailand.

Atmospheric deposition is the primary source of Hg in remote environments. Additionally, soil is another primary receiver of atmospheric Hg deposition in terrestrial ecosystems. Moreover, Hg can be retained by soil over long periods because of its elemental impurities (Tun et al., 2020). Hg contents found in samples from Myanmar and the Philippines exceeded the standard limits of 1 μg/g in the US (California), 6.6 μg/g in Canada, and 0.83 μg/g in the European Union (Netherlands) (Guney et al., 2020).

Plants use their radicle system to absorb organic and inorganic Hg forms, which are then delivered to the leaves (Hanson et al., 1995). Temmerman et al. (De Temmerman et al., 2009) found that Hg absorption also occurs through plant roots, depending on soil exposure levels to Hg. Another theory is that Hg from the atmosphere can accumulate in most plants (Patra & Sharma, 2000). Based on the findings of this review, the Hg levels found in the studied areas were higher than those reported in the Lanmuchang Hg mining area, Guizhou Province, China (0.175 μg/g w.w.) (Feng & Qiu, 2008). Meanwhile, the reported Hg concentrations in vegetable samples collected at the Idrija Hg mining area in Solvenia, were < 0.215 μg/g w.w. (Kobal et al., 2017). Compared with a study in the Alacran mine, Colombia where the maximum value of Hg found in a leaf was 2.78 μg/g d.w., the values reported in the reviewed studies were higher. In addition, the Hg levels found in plant samples from the Almadén mining district, Spain, showed extremely high values in leaves, in the range of 0.16 – 1,278 μg/g (Higueras et al., 2006).

Fish in polluted water bodies are potentially contaminated by Hg. The reviewed studies investigated fish species, obtained from local markets and fishermen within ASGM areas. Although the levels of Hg in some fish samples were below the WHO standard limits (0.5 μg/g w.w.), the Hg levels in fish from fishermen sources in Indonesia and Cambodia were very high. Generally, more than 75% of the Hg accumulated

accumulated in the muscle tissues of freshwater fish is in the organic form of MeHg (Zhang & Wong, 2007). Moreover, seasonal variation such as precipitation should be considered, as there is a wide variety of aquatic habitats in the studied regions, which are affected by seasonal variations. For example, floods can temporarily modify the biogeochemical components (e.g., oxygen content, pH, and prey availability) of a system. Thus, the fish-sampling condition with respect to season (e.g., during dry or wet season) is important. We therefore suggest that people living near ASGM areas should practice caution when consuming fish.

Hg concentration in human hair have been associated with both the endogenous Hg contamination through consumption of food that were contaminated by Hg species and the Hg concentration in the air because elemental Hg can adhere to human hair (Kobal et al., 2017; Li et al., 2008). The Hg concentrations in human hair samples from the studied ASGM areas in Cambodia, Myanmar, and Thailand were lower than those of residents of the Wuchuan Hg mining area, China, (mean value and range of 34 and 7.6 –93.1 μg/g, respectively) (Feng & Qiu, 2008). The lower Hg level may be attributed to lower susceptibility of human hair for Hg vapor (Kawakami et al., 2019). In addition, Hg mining areas in Guizhou Province and valley in the southern part of Shaanxi Province in central China showed Hg levels with mean values of 4.3 μg/g (1.6 – 12.6 μg/g) (Jia et al., 2017). However, the Hg content found in the hair samples from the ASGM area in Lebaksitu, Indonesia and the Acupan region, the Philippines showed concentrations of 0.84 – 9.015 and 0 – 26.6 μg/g, respectively. Those value were above the allowable limit as per the WHO guidelines. Meanwhile, the Hg concentrations found in Cambodia, Myanmar, and Thailand were within the recommended limit. In addition, a study re-ported links between

high fish consumption and burning gold-amalgam exposure to high levels of Hg in human hair.

In an ASGM process, the final stage is the most critical in Hg inhalation because miners are exposed Hg vapors during amalgamation burning. The average Hg concentration in the air of Palu city, Indonesia, was 12,782 ng/m^3 (Nakazawa et al., 2016). The study indicated that 93% of the population was above the no risk HQ ratio. Therefore, both miners and nearby residents were at the risk of adverse health effects resulting from inhalation Hg vapor (Nakazawa et al., 2016).

A study in Myanmar conducted a health inspection around an ASGM area in the Mandalay region. Based on the Human Biomonitoring Commission Standard, seven miners were in the range of warning status. Furthermore, the study highlighted that 16% of miners showed signs of Hg poisoning, such as nervous system damage, whereas nonminers did not demonstrate aberrant symptoms (Kyaw et al., 2020).

A study in the Philippines conducted physical examinations on 163 children. All children showed the following common abnormalities: lower than average height, gingival discoloration, lower than average weight, adenopathy, and dermatologic abnormalities. According to the WHO, an adult who and 200 mg/day of Hg (e.g., from fish) has a 0.3% and 8% chance of experiencing paresthesia symptoms, respectively (von Burg, 1995).

In the Phanom Pha gold mining area, Thailand, the Hg exposure of miners and schoolchildren after ASGM activities was investigated. The HQ, to a reference dosage (0.0003 mg/kg/day), was below the level at which unfavorable health effects on miners should be predicted (Umbangtalad et al., 2007). The high exposure miner group and

schoolchildren showed the HQ raios of 16–218 and 0.02–0.23, respectively. Inhalation of gold-amalgamation vapor can accumulate in the brain and kidneys (Umbangtalad et al., 2007). Indeed, a study reported that miners in Brazil who used the open burning method without using a Hg-retort showed Hg levels that were higher than the normal Hg concentration in urine with using a Hg-retort (Umbangtalad et al., 2007).

5. Conclusions

This review assessed and identified the Hg pollution in the ASGM areas of Myanmar and some other relevant Southeast Asian countries. Research should continue to focus on the current situation of ASGM activities in the studied countries and other parts of the world that allow ASGM activities because Hg is released by ASGM areas, which is a persistent and toxic global pollutant that can be transported through the atmosphere and deposited in terrestrial and aquatic ecosystems. The study aims to contribute to further research activities such as health inspection and Hg management from ASGM areas because Hg is still used in ASGM activities. For example, Myanmar has not recognized the national Hg inventory and its research activities are still limited. Additionally, Myanmar is still not a part of the Minamata Convention. Because gold prices remain high, despite countries like Indonesia ratifying the Minamata Convention, Hg demand is still high in ASGM activities.

According to these reviewed studies, it is evident that Hg continues to cause contamination in the vicinity of ASGM areas, including nearby residential areas. Human epidemiological assessments on Hg related diseases should be undertaken on a regular basis in the ASGM areas. Hg-contaminated areas should be controlled using reasonable regulations, policies, and frameworks. In addition, innovative Hg-free processing technologies and alternative economies should be introduced to support ASGM

communities to reduce Hg emissions. Consequently, awareness of Hg problems can effectively reduce Hg pollution in ASGM communities.

Chapter III

Assessment of Hg Pollution in Urban and Suburban Areas in Myanmar

1. Introduction

Increased population have recently occurred in Myanmar (Review, 2023), especially Yangon and Mandalay. In the late 2010s, Myanmar has been fasting growing economy with annual GDP growth of 7.3%. Meanwhile, Yangon and Mandalay contributed 22 % and 11.5% of the country's Gross Domestic Product (GDP) from 2011 to 2015 (Kyaw, 2017). Myanmar's cities' crucial economic zones are experiencing development in urbanization and industrialization. Furthermore, it has been increasing in-vehicle amounts, and the urban area's traffic densities have been growing. On the other hand, many different types of industries, such as steel production, metal smelting, textile, beverages manufacturing, and construction activities, have been implemented, especially in the major cities of Yangon and Mandalay.

It has been report'd that metal pollution has affected groundwater, drinking water, air quality, soil, and human urine and hair in Myanmar (Kawakami et al., 2019; Kuang et al., n.d.; Kyaw et al., 2020; Mar, 2020; Osawa & Hatsukawa, 2015; Soe et al., 2022; Tun et al., 2020; Wongsasuluk et al., 2021). Moreover, urban pollution was indicated by analysis of polycyclic aromatic hydrocarbons (PAHs) in road dust from some urban and rural areas in Myanmar (Mon et al., 2020). However, information on Hg pollution and its human health risk assessment by Hg exposure from urban areas in Myanmar is not available so far.

Therefore, this chapter analysed Hg concentrations in road dust from urban and suburban sites in Myanmar to understand the contamination status by Hg.

2. Materials and Methods

2.1. Sample Collection

Thirteen-nine road dust samples and 74 sediment samples were collected in urban areas such as Yangon and Mandalay and sub-urban areas such as Pathein, Expressway Chaungtha, and Wundwin in Myanmar in December (dry season) of 2014, 2015, 2016, and 2018. The sampling points of road dust and sediment are shown in Figure 2.1 and Figure 2.2, respectively. Samples were collected from main roads and sides roads using plastics brushes and dust pan. All samples were transported to laboratory with ice pack and were kept in -25°C until further chemical analysis.

3.6. Analytical Procedure of Hg

All samples were air-dried for a week at room temperature, sieved using a nylon sieve with < 2mm, and removed small debris. Subsequently, the samples were grinded using an agate mortar and pestle for the homogeneous mixture, then stored in sealed polyethylene bags for the prior analysis.

According to the analysis of Hg in road dust and sediment samples, 0.2 g samples were weighted and added to ceramic boat. Mercury was analysed using a heat thermal atomic absorption spectrometer (HT-AAS; MA 3000, Nippon Instrument Cooperation). For the accuracy of analytical procedures, a certified reference material CRM 7302-a (trace elements in marine sediment) by National Metrology Institute of Japan (NMJI) was analysed. The recovery and precision (n = 3) of Hg was 98-100 %.

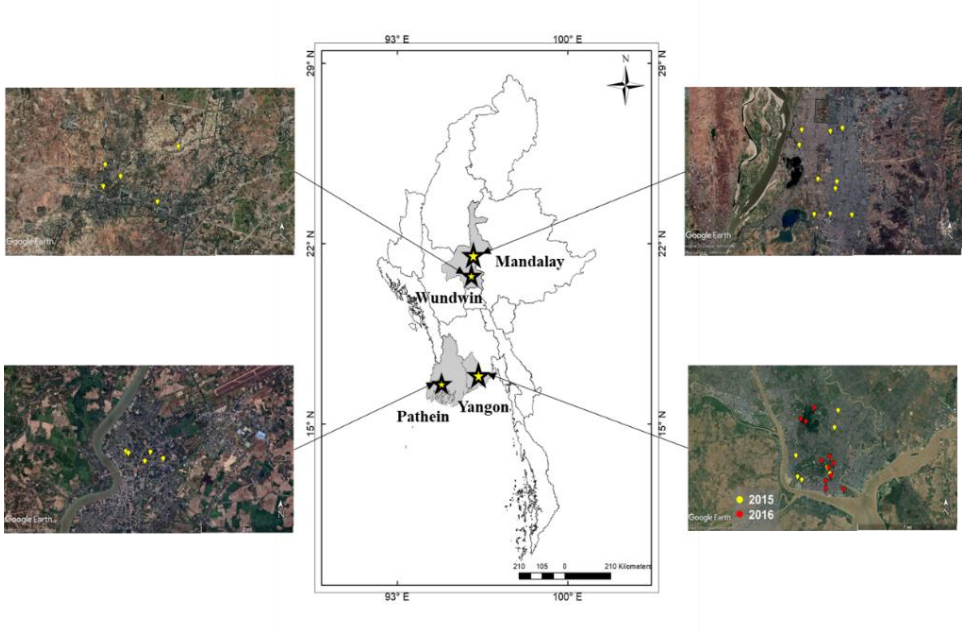

Figure 2.1. Sampling points of road dust in urban and suburban areas of Myanmar.

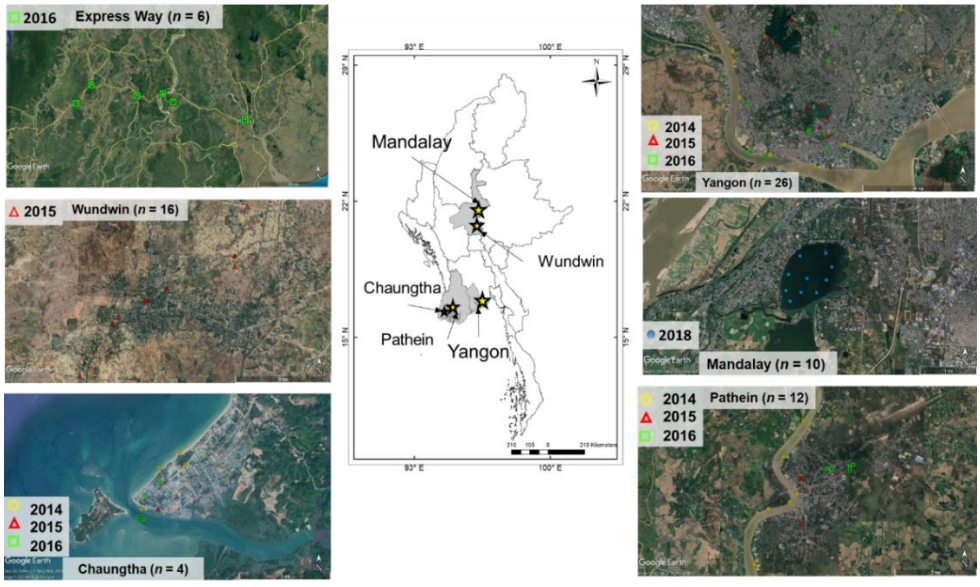

Figure 2.2. Sampling points of sediment in urban and suburban areas of Myanmar.

3.6. Statistical Analysis

Because metal concentration data were not normal distribution, the data were log-transformed. One-way ANOVA for evaluating difference of Hg concentrations among locations. Statistical analysis was performed using R studio (2022.12.0).

3. Results and Discussion

3.1. Hg Concentration in Road Dust

Mercury concentrations in 39 road dust samples from urban and suburban areas in Myanmar are shown in Table 2.1. In general, Hg concentration was the highest from Mandalay among the locations (Figure 2.3). The concentrations in road dust from Yangon and Manladay were significantly higher than those from Patein and Wundwin (Figure 2.3). These results indicate urban pollution by Hg, especially in Mandalay. Previous studies found that Hg concentrations was high in urban road dust influenced by vehicle sources, industrial activities, and coal burning activities and so on (Benhaddya et al., 2016; Kaonga et al., 2021).

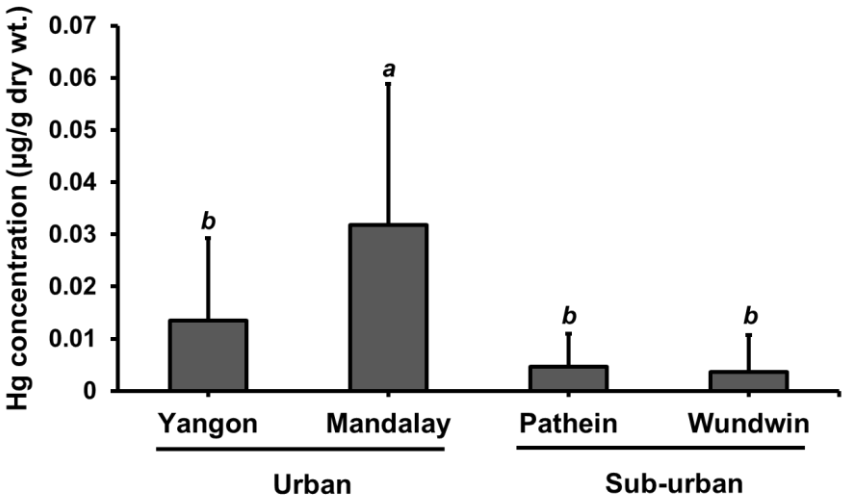

Figure 2.3. Hg concentration in road dust from Myanmar. Different letters mean significant difference at $p < 0.01$.

3.2. Comparison of Hg Concentration in Road Dust with Other Countries

Mercury concentrations in urban and suburban areas from Myanmar were compared with other studies from different countries (Table 2.1). For the comparison, particle size (0.5 – 2 mm) of road dust was fixed, because Hg concentrations normally are higher in fine particles (Loganathan et al., 2013). Hg concentrations in road dust from Myanmar were equal or lower than those from other studies. However, Hg concentrations in this study were lower than previous studies.

These differences can be related to economic conditions, industrial emission rates, urbanization as well as geochemical characteristics (Han & Lu, 2017; Lima et al., 2023a; Žibret, 2019). A study reported that level of Hg in road dust can be influenced by different human activities such as traffic and burning activities depending on the population density (Khademi et al., 2020). Here, we focused population in the cities as human activities and hypotheseized that higher population correspond to increase of Hg pollution. Fig. 2.4 shows the relationships between Hg concentrations in road dust and population from

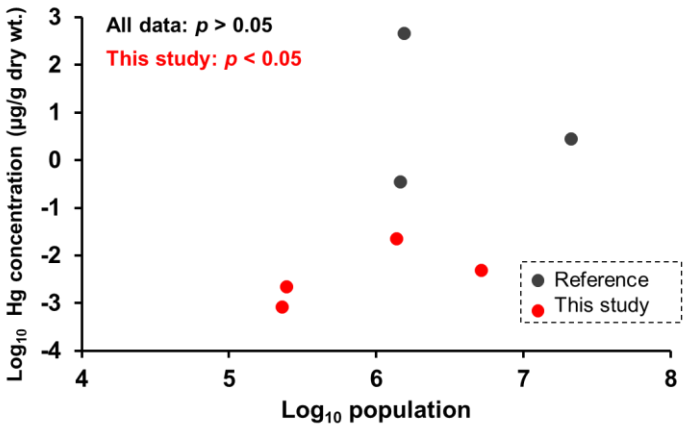

Figure 2.4. Relationship between population and Hg concentrations in road dust from Myanmar and other studies (Wang, 2021; Harb et al., 2015; Kara, 2020; Lima et al., 2023; Zgłobicki & Telecka, 2021).

Table 2.1. Comparison of Hg concentration (μg/g) in road dust with other countries.

Countries	Population	Particles size	Sampling sources	Value	Hg	Reference
Abu Dhabi, UAE	1,452,000	2 mm	Highway	Mean	0.36	Al-Taani et al., 2019
Jining, China	1,544,000	< 2 mm	Urban	Mean	460.8	Dai et al., 2023
Beijing, China	20,897,000	1 mm	Urban	Mean	2.83	Wang, 2021b
Yangon, Myanmar	5,157,000	2 mm	Urban	Geomean	0.005	Present study
Mandalay, Myanmar	1,374,000	2 mm	Urban	Geomean	0.022	Present study
Pathein, Myanmar	245,810	2 mm	Suburban	Geomean	0.002	Present study
Wundwin, Myanmar	229,760	2 mm	Suburban	Geomean	0.001	Present study

cities cited. The results of our analysis revealed significant positive correlations between Hg and population size in our study. However, there was no association with the other reference studies. As described earlier, population and economic growth in Myanmar is increasing. Therefore, further contamination by Hg are considered in future.

3.3. Hg Concentration in Sediment

Mercury concentrations in 74 road dust samples from urban areas of Yangon and Mandalay, as well as suburban areas of Pathein, Wundwin, Chaungtha, and Wundwin in Myanmar, are presented in Figure 2.5. Hg showed the highest concentration, particularly

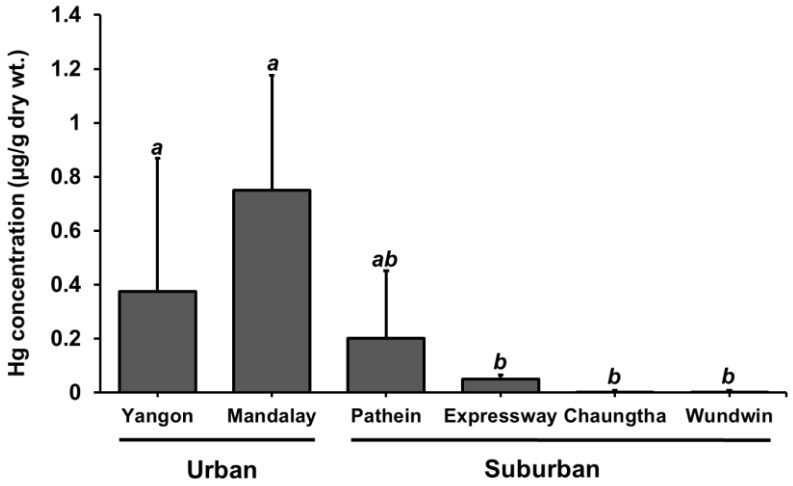

Figure 2.5. Hg concentration in sediment from Myanmar. Different letters mean significant difference at $p < 0.01$.

in the Mandalay area as like Hg concentration in road dust, may be attributed to various sources. Proshad et al., 2022 reported that Hg in urban areas can be linked to anthropogenic activities such as coal-fired processes, power generation, municipal solid waste disposal, and medical waste. This is because industrial waste may be directly discharged into water bodies and the surrounding environment. Previous studies (Ogundele & Ayeku, 2020) have discussed that Hg can be distributed into sediment due to atmospheric deposition and coal-burning activities. Consequently, Hg tend to be more concentrated in urban areas in Myanmar. Therefore, the study suggests that urban pollution by Hg contamination in sediment is a concern in Myanmar.

3.4. Comparison of Hg Concentration in Sediment with Other Countries

Mercury concentrations in sediment samples from Myanmar were examined and compared to those in other countries, as shown in Table 2.2. For instance, the concentrations of Hg in this study were notably higher than those found in Bangladesh, Brazil, China, and Korea, with the exception of Ghana. The variation in mercury

Table 2.2. Comparison of Hg concentration (μg/g) in sediment with other countries.

Countries	Population	Sampling Sources	Hg	References
Jalpaiguri, Bangladesh	540,000	Urban river	0.17	Proshad et al., 2022
Ribeirão Preto, Brazil	12,300,000	Urban	0.01	MacHado et al., 2016
Shanghai, China	24,500,000	Urban	0.06	Wang et al., 2015
Bono, Ghana	2,770,000	Urban	1.24	Nyantakyi et al., 2019
Ulsan, Korea	1,120,000	Urban	0.02	Jeong et al., 2021
Yangon, Myanmar	5,400,000	Urban	0.36	This study
Mandalay, Myanmar	1,400,000	Urban	0.75	This study
Pathein, Myanmar	240,000	Suburban	0.2	This study
Chaungtha, Myanmar	11,000	Suburban	0.003	This study
Wundwin, Myanmar	220,000	Suburban	0.001	This study

concentration levels in sediment between countries results from complex interactions between natural processes and human activities.

In the Ghanaian study, Hg concentrations were higher than those observed in our study, primarily due to significant contributions from industrial and agricultural effluents. Several factors can influence Hg concentrations in sediment, including geological characteristics, waste discharge, atmospheric deposition, and climate-related factors. Similar to road dust, we examined the relationships between Hg concentrations in road dust and population from other studies in Figure 2.6. The results showed a significant positive correlation in this study, but there was no significant correlation with the findings

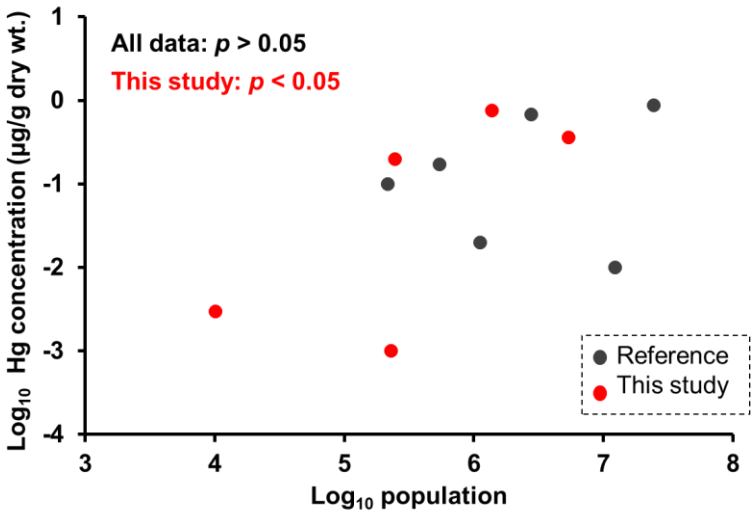

Figure 2.6. Relationship between population and Hg concentration in road dust from Myanmar and other studies (Proshad et al., 2022; MacHado et al., 2016; J. Wang et al., 2015; Nyantakyi et al., 2019; Jeong et al., 2021).

Of other studies. Therefore, we conclude that a higher population can also be a contributing factor to the influence of Hg pollution in our study.

3.5. Ecological Risk

In this study, Hakanson potential ecological risk index method was used to assess the ecological risk of Hg in the sediments from urban area and suburban area of Myanmar (Hakanson, 1980). The index was the highest ranges from 0.39 to 374.95 particularly from urban area of Mandalay as (Figure 2.7). Hg in sediment can affect the teratogenic on the embryos of the aquatic organisms due to its strong toxicological effects (Cheng et al., 2022).

Therefore, the results outlined above indicate a significant ecological hazard posed by Hg. In the study area of Mandalay, the risk level ranged from moderate to

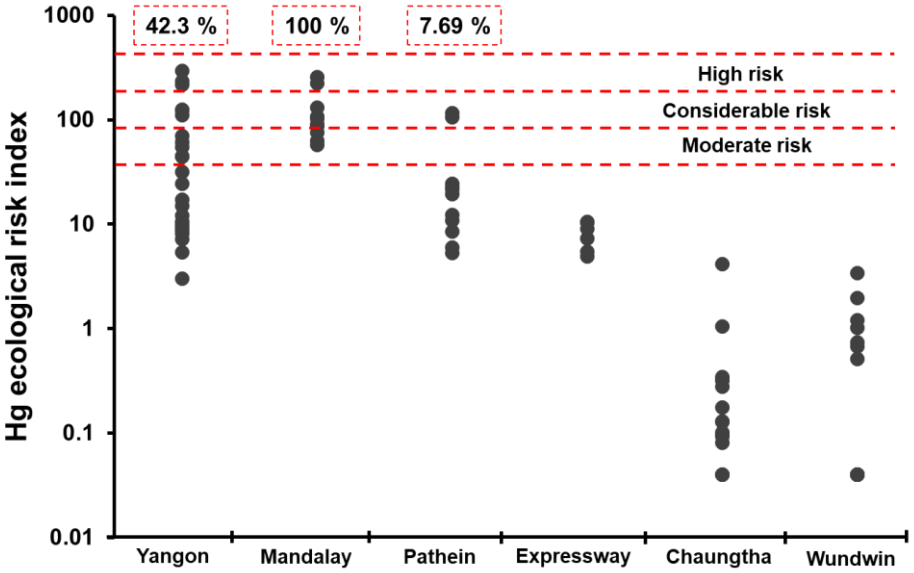

Figure 2.7. Potential ecological risk assessment of Hg in sediment.

Considerable, while Yangon exhibited a moderate risk. Pathein was considered to have a lower moderate risk, and other areas showed low risk.

4. Conclusions

This study revealed that Hg in road dust and sediment were observed in urban areas of Yangon and Mandalay and the sources was estimated by vehicle, municipal waste and industrial emissions.

Moreover, Hg in road dust and sediment contains several limitations. We did not obtain and analyse potential source samples such as vehicle exhausts, tires, brake pad, gasoline, air particle, and soil to make clear vehicle and industrial effects. Therefore, further detailed investigation in Myanmar is required to validate our results. Nevertheless, we believe that this study can provide useful baseline information on metal pollution in Myanmar.

Chapter IV
Sources of Hg in Urban and Suburban Area

1. Introduction

In the previous chapter, we discussed that metals in urban areas can originate from various sources. The transformation of urban areas in Myanmar can lead to various environmental changes, including concerns related to metal contamination, such as mercury contamination. This chapter aims to estimate the sources of mercury contamination by analysing other metals.

2. Materials and Methods

2.1. Analytical Procedure of Metals

All samples were air-dried for a week at room temperature, sieved using a nylon sieve with < 2mm, and removed small debris. Subsequently, the samples were grinded using an agate mortar and pestle for the homogeneous mixture, then stored in sealed polyethylene bags for the prior analysis.

According to the analysis of Hg in road dust and sediment samples, 0.2 g samples were weighted and added to ceramic boat. Mercury was analysed using a heat thermal atomic absorption spectrometer (HT-AAS; MA 3000, Nippon Instrument Cooperation). For further analysis of other metals, each of road dust and sediment samples of 0.1 g was added to Teflon vial and was digested with 9 ml of HNO_3 and 1 ml of HF using a microwave digestion system (ETHOS EASY, Milestone General). Afterward, the sample was heated to remove the acid and the residue was dissolved in 5 ml of HNO_3. Concentration of 30 metals (Li, Be, Al, V, Cr, Mn, Fe, Co, Cu, Zn, Ga, As, Se, Rb, Sr, Mo, Ag, Cd, In, Sn, Sb, Te, Cs, Ba, Gd, Pt, Tl, Pb, Bi, U) in the digested samples was measured with an inductively coupled plasma mass spectrometer (ICP-MS; Agilent 7800, Agilent Technologies). For the accuracy of analytical procedures, a certified reference

material CRM 7302-a (trace elements in marine sediment) by National Metrology Institute of Japan (NMJI) was analyzed. The recovery and precision (n = 3) of Hg was 98-100 %.

2.2. Principal Component Analysis (PCA)

Principal component analysis (PCA) was also conducted by using the normalized rotation method. All component scores included information on all the metals as a single number. The PCA identify patterns and correlations in the data, allowing pinpoint potential sources of the study areas.

3.6. Positive Matrix Factorization (PMF)

Positive Matrix Factorization (PMF) receptor model is useful tool to identify metals contribution and source apportionment from the urban road dust (Norris, G.A., Duvall, R., Brown, S.G., Bai, 2014). The model was performed by the EPA PMF 5.0 (Norris, G.A., Duvall, R., Brown, S.G., Bai, 2014). As a multivariate factor analysis tool, the USEPA developed the receptor model to estimate individual species. The equation (1) is defined as follows:

$$X_{ij} = \sum_{k=1}^{P} g_{ik} f_{kj} + e_{ij} \quad (1)$$

Where, X_{ij} is the concentration of $i_{samples}$ and $j_{species}$; P is the number of factors; k is considered constant of each source; g_{ik} refers to the relative contribution of factor k; f_{kj} is the profile factor of each source; e_{ij} refers to the PMF residual error of the sample and species.

Furthermore, to clarify the factor contributions and profiles in the PMF model, the function Q is defined as the following equation (2):

$$Q = \sum_{i=1}^{n}\sum_{j=1}^{m}\left(\frac{X_{ij} - \sum_{k=1}^{p} g_{ik}f_{kj}}{u_{ij}}\right) \quad (2)$$

Where, n is the number of samples; m is the number of species; u_{ij} refers to the uncertainty of the analyzed concentration for the i_{sample} and $j_{species}$.

Furthermore, in order to load the uncertainty, the method needs the limit of detection (LOD) for the individual species for estimating the uncertainty value. The equations (3 and 4) are defined as follows:

If $Xij \leq MDL$; $U_{ij} = \frac{5}{6} \times MDL$ (3)

If $Xij \geq MDL$; $\sqrt{(\text{error fraction} \times \text{concentration})^2 + (0.5 \times MDL)^2}$ (4)

Where, MDL is the method of detection limit and error fraction is the measurement uncertainty in percentage (Norris, G.A., Duvall, R., Brown, S.G., Bai, 2014; Tan et al., 2016).

3. Results and Discussion

3.1. Source Identification of Hg in Road Dust

To characterize metals in road dust, PCA was applied in this study. Previous studies reported that metals from natural and anthropogenic sources were estimated by the scores of principal components (PC) loadings (Aguilera et al., 2021; Borůvka et al., 2005; Gu & Gao, 2018; Sundaray et al., 2011; Zhang et al., 2009).

In this study, 57.4% of the total variance was explained by two PCs (PC1 and PC2), accounting PC1 for 42% and PC2 for 15.4% (Fig. 3.1). PC1 explained that all metals were positive and loading scores of almost all sampling points in urban areas (Yangon and Mandalay) were also positive, indicating that PC1 represents metal pollution

level. This result was partly supported by regional differences in Hg concentration shown Table 2.1 in Chapter 3. On the other hand, PC2 clearly segregated the northern regions (Mandalay and Wundwin) from the southern regions (Yangon and Pathein), potentially due to the geographical background conditions of the study areas.

PMF was also conducted to determine the source of metals in sampling areas. Based on the error estimation of the model, four factors were fitted for identifying the source apportionment and contribution of metal profile in road dust (Fig. 3.2). Factor 4 was the most reliable factor (90%) accounted for Al (68.0 %), Rb (64.1 %), Sr (53.9 %), Gd (52.7 %), and Tl (50.0 %). These metals are naturally rich elements in the earth's crust (Anke & Angelov, 2004; Junhong Bai et al., 2011; Gu et al., 2016; Gu & Gao, 2018), suggesting that factor 4 is natural sources. Factor 2 (89%) was mainly composed by Ag (69.4 %), Zn (65.5 %), Mo (59.2 %), Cd (56.6 %), Cu (46.1 %), and Pb (38 %)(Fig. 4). Silver can be observed in household tools like mirrors and other electricity industries (Briffa et al., 2020). Several studies reported that Zn, Cu, Cd, and Pb are considered the dominant metals relating to the industrial (metal processing), coal combustion, and vehicular (lubricants oil, exhausts, use of brake pads and tear of tires) (Liu et al., 2017; Othman, 2020; Soltani et al., 2015; Tian et al., 2018). Therefore, factor 2 may represent anthropogenic sources like the vehicle and industrial emissions.

Although factors 1 (63 %) and 3 (70 %) were extracted by PMF model, the both reliabilities were relatively low compared with factors 2 and 4 (Fig. 3.2), there was a notable disparity in metal contritubions. For factor 1, Te (90%) was the most contribution metal followed by Li (45 %) and Bi (40 %), while factor 3 was explained by Hg (51 %), Cr (51 %), Sn (43 %), and Fe (41 %). However, metal sources of factors 1 and 3 were not clearly identified. Nevertheless, we hypothesized that the sources of Hg likely originate

from a combination of natural and anthropogenic sources, including activities such as household waste burning and the improper discharge of municipal waste. As a result, this study primarily focused on factors 2 and 4 in further discussion, given their well-fitted model.

Contributions of factors extracted by PMF model in each area are shown in Fig. 3.3. Factor 4 contribution was clearly high in Mandalay and Wundwin. As mentioned earlier, factor 4 indicates natural source (Fig. 3.2). PCA results showed that Al, Rb, Sr, Gd, and Tl explained by factor 4 were distributed in PC2 positive (Fig. 3.1), meaning difference between northern and southern parts and especially among of the metals, Rb concentration was significantly higher in Mandalay and Wundwin than Yangon and Pathein. These results imply background difference between northern and southern parts in investigation sites. Factor 2, which is reflected as vehicle and industrial emission sources, was relatively high contribution in urban areas like Yangon and Mandalay. Silver, Zn, Mo, Cd, Cu, and Pb in factor 2 were high concentrations in Yangon and Mandalay (Table 2.1) and showed PC1 positive correlation according to PCA result (Fig. 3.1). Mon et al., 2020 revealed that high concentration of PAHs was observed in road dust from Yangon because of vehicle emissions. Moreover, a $PM_{2.5}$ study found that vehicle and biomass-burning activity can be significant sources in urban areas of Yangon and Mandalay (Zhang et al., 2022). Therefore, urban pollution by metals is considered in Yangon and Mandalay.

3.2. Source Identification of Hg in Sediment

Similar to road dust, sediment samples from urban and suburban area from Myanmar was estimated by PCA and PMF (Figures 3.4 and 3.5). Two PC explained 78.3 % of the total variance. PC1 (64.3 %) was characterized by high positive loadings

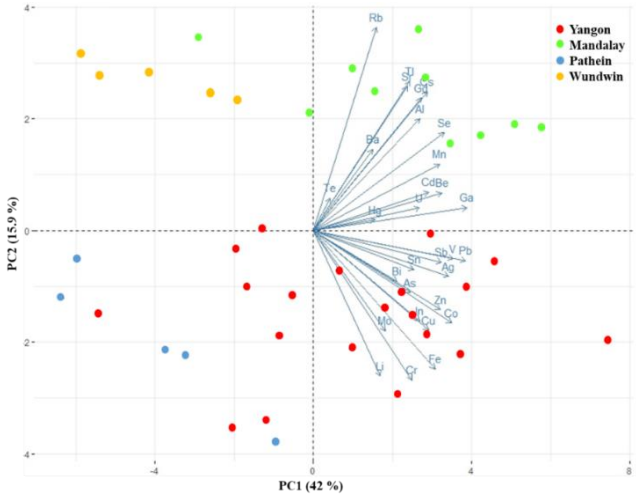

Figure 3.1. Principal component analysis of metal concentrations in road dust from urban and suburban areas of Myanmar.

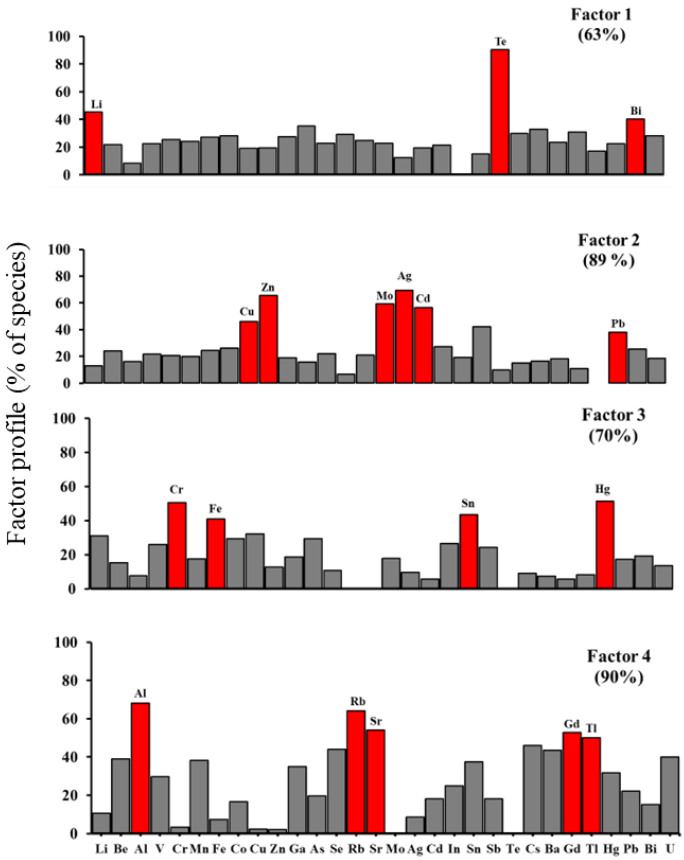

Figure 3.2. Metals by factor profile in road dust from urban and suburban areas of Myanmar.

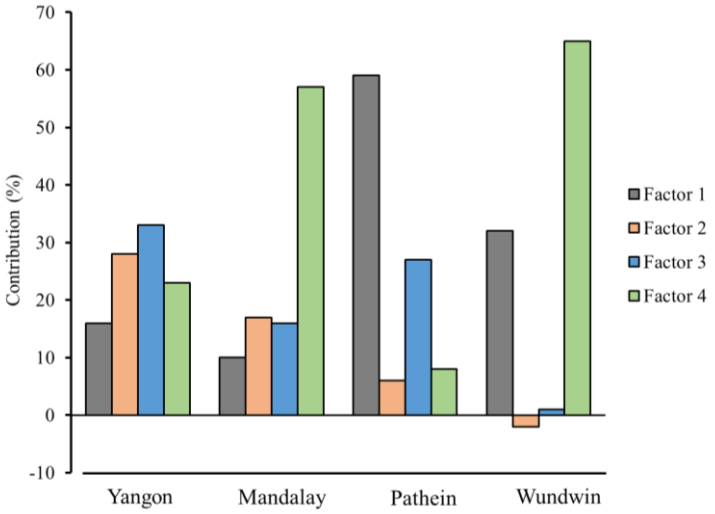

Figure 3.3. Factors contribution in each area of Myanmar in road dust.

For all metals, including mercury. The positive highly associations between Hg and other metals such as Ag, Pb, Sn, Sb, Cd, and Cu metals suggest a common anthropogenic sources, especially from urban area of Yangon and Mandalay likely coal burning activities, vehicle emissions, industrial activities, and atmospheric deposition.

On the other hand, PMF model were extracted for four factors. All factors were fitted and reliable to the model. Factor 1 presented as Hg (89%) was the highest contributions, related to human activities such as coal burning, municipal solid wastes and waste incinerator. As for the other metals such as such as Ag (75%), Cd (62%), Sb (59), Zn (53%), Mo (52%), Sn (52%), Pb (52%), and Cu (51%) were linked to industrial and vehicle emissions.

Factor 2 explained Te and Pt was highly contributing, particularly in Pathein. Pathin is compared to Yangon and Mandalay; it is low human activities and point sources. However, Te and Pt can be released from improper waste discharge and atmospheric deposition sources.

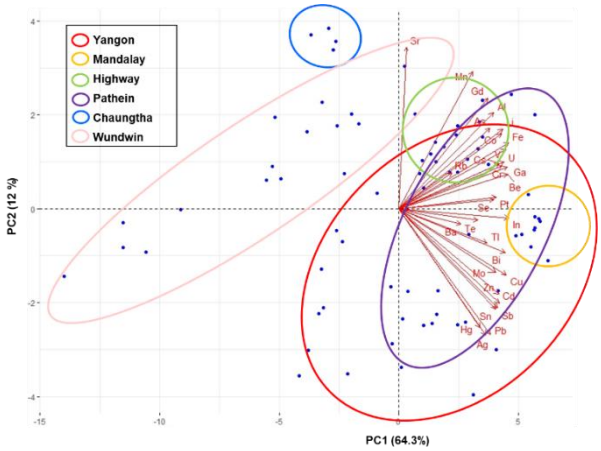

Figure 3.4. Principal component analysis of metal concentrations in sediment from urban and suburban areas of Myanmar.

Factors 3 and 4 were highly contributed by Mn, Gd, Al, and Sr which are abundance of elements in earth's crust. Elements in the upper crust can contribute to the soils and sediment during the geological process such as erosion and weathering. Therefore, factor 3 and 4 can be associated with the natural souces, particularly in suburban areas of Expressway, Chaungtah, and Wundwin.

As we discussed earlier, Factor 1 is considered as urban pollution by anthropogenic activities, especially in Yangon and Mandalay. In addition, Hg revealed the highest contributed among the metals in factor 1, indicating Hg may stem from the anthropogenic activities like coal burning, vehicle emissions, industrial processes, and municipal waste. Factor 2 can be considered as mixed sources from Pathein and factor 3 and 4 were considered as natural sources from Expressway, Chaungtah, and Wundwin in Figure 3.6.

This chapter discusses the source estimation of Hg and other metals in road dust and sediment from urban and suburban areas of Myanmar. The study reveals that urban pollution from road dust, Factor 3 was attributed to Hg (51%), Cr (51%), Sn (43%), and

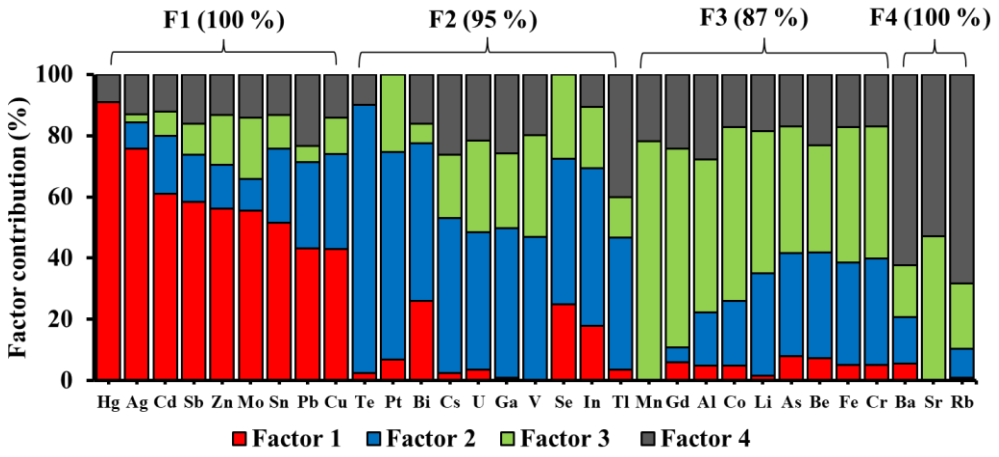

Figure 3.5. Factor profile by PMF model for sediment

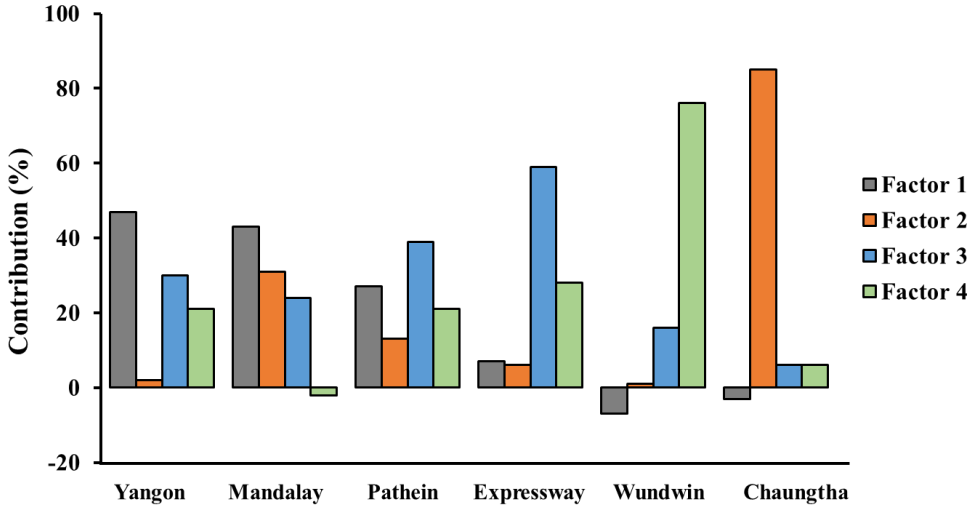

Figure 3.6. Factor contribution in each area of Myanmar in sediment.

Fe (41%). Despite this, the sources of metals in factors 3 remained unclear. Nonetheless, we hypothesized that the origins of Hg could possibly be a blend of both natural and anthropogenic sources, encompassing activities like household waste burning and improper municipal waste disposal. Furthermore, Factor 2 indicated vehicle and industrial emission sources, significantly contributes to the high levels of Ag, Zn, Mo, Cd, Cu, and Pb in Yangon and Mandalay.

Moreover, it is important to note that sediment samples raise more concerns than road dust samples due to the moderate ecological risk observed in urban areas. Factor 1, dominated by Hg (89%), showed the highest contributions and was associated with human activities like coal burning, municipal solid waste, and waste incineration On the other hand, metals such as Ag (75%), Cd (62%), Sb (59%), Zn (53%), Mo (52%), Sn (52%), Pb (52%), and Cu (51%) were assumed by industrial and vehicle emissions. Consequently, our study underscores the presence of metal pollution in urban areas of Myanmar.

Chapter V

Health Risk Exposure by Hg in Urban and Suburban Areas in Myanmar

1. Introduction

Road dust in urban environments often contains Hg which can concerns about potential human health risks. In Myanmar, urbanization and industrialization have being increasing recently. According to these progresses, the vehicle activities, coal burning activities, construction and industrial activities can contribute the accumulation of Hg in road dust. Therefore, the study aims to assess the human health risk by Hg exposures through the dust.

2. Materials and Methods

To assess the noncarcinogenic risks associated with road dust exposure, a health risk assessment of exposure to both adults and children was conducted using the United States Environmental Protection Agency (USEPA) model (US EPA, 2002; Van den Berg, 1994). Three exposure routes of Hg from dust ingestion, inhalation, and dermal absorption by skin were considered (De Miguel et al., 2007). Based on the handbook of exposure factors, we calculated the daily intake (DI, mg kg^{-1} day^{-1}) of metals through each path using the following formula (5) – (7) (USEPA, 1989, 1996):

$$DI_{ing} = \frac{C \times IngR \times EF \times ED \times 10^{-6}}{AT \times BW} \quad (5)$$

$$DI_{inh} = \frac{C \times InhR \times EF \times ED}{PEF \times AT \times BW} \quad (6)$$

$$DI_{dermal} = \frac{C \times EF \times ED \times SA \times AF \times ABS \times 10^{-6}}{AT \times BW} \quad (7)$$

Where C is concentration (μg/g) of metals in road dust; ingestion rate (IngR) indicates rate of road dust ingestion; EF (day/yr) and ED (yr) are exposure frequency and exposure duration, respectively; AT is average time of lifespan; BW (kg) is body weight; Inhalation rate (InhR) represents rate of human inhalation of road dusts; PEF is particle emission factor; SA, AF, and ABS represent dermal exposed skin area, dermal adherence, and dermal absorption factor, respectively. The parameter of the index's values and reference dose (RfDs) of metals from ingestion, inhalation and dermal contact were considered (Tables 1 and 2). Hazard quotients (HQ) was obtained by following eqations (8-10).

$$HQ_{ing} = DI_{ing}/RfD_{ing} \quad (8)$$

$$HQ_{inh} = DI_{inh}/RfD_{inh} \quad (9)$$

$$HQ_{dermal} = DI_{dermal}/RfD_{dermal} \quad (10)$$

Hazard index (HI) is sum of HQ for all selected metals from three exposure pathways (USEPA, 2001). If the HI value exceeds one, non-carcinogenic effects are assumed. If the HI is below one, indicating no significant risk. The equation for HI was determined as follows (11).

$$HI = HQ_{ing} + HQ_{inh} + HQ_{dermal} \quad (11)$$

Table 3.1. Indicators and values for evaluating the human health risk models in road dust.

Indicators	Description	Value		Reference
		Adults	Children	
IRS (mg/day)	Ingestion rate	50	100	USEPA, 2011
EF (day/yr)	Exposure frequency	350		USEPA, 2004
ED (yr)	Exposure duration	30	6	USEPA, 2004
BW (kg)	Average body weight	57.7	16.8	Dang et al., 2010
InhR (m^3/day)	Inhalation rate	20	7.6	USEPA, 2011
SA (cm^2)	Skin area	5700	2800	USEPA, 2004
AF (mg/cm^2)	Skin adherence factor	0.07	0.2	USEPA, 2004
PEF (m^3/kg)	Particle emission factor	1.36×10^9		US EPA, 2002
AT (day)	Average time of lifespan (365*ED)	10950	2190	USEPA, 2004
ABS_d	Dermal absorption	0.001		USEPA, 2004

Table 3.2. Reference dose value (mg/kg/day) for ingestion, inhalation, and dermal exposure.

Element	RfD_{ing}	RfD_{inh}	RfD_{dermal}	Reference
Hg	3.00×10^{-4}	8.57×10^{-5}	2.00×10^{-5}	Juan Bai & Zhao, 2020; USEPA, 2004

3. Results and Discussion

According to Hg concentrations in road dust, we assessed the noncarcinogenic human health risk by Hg exposures from road dust. Among three exposure pathways, ingestion was the predominant (More than 90%) see in Figure 4.1.

HI values for children were higher than those for adults, suggesting that children are at higher risk (Figure 4.2). However, HI for adults and children were less than one, suggesting less harmful effect on human health by Hg exposure through road dust in Myanmar.

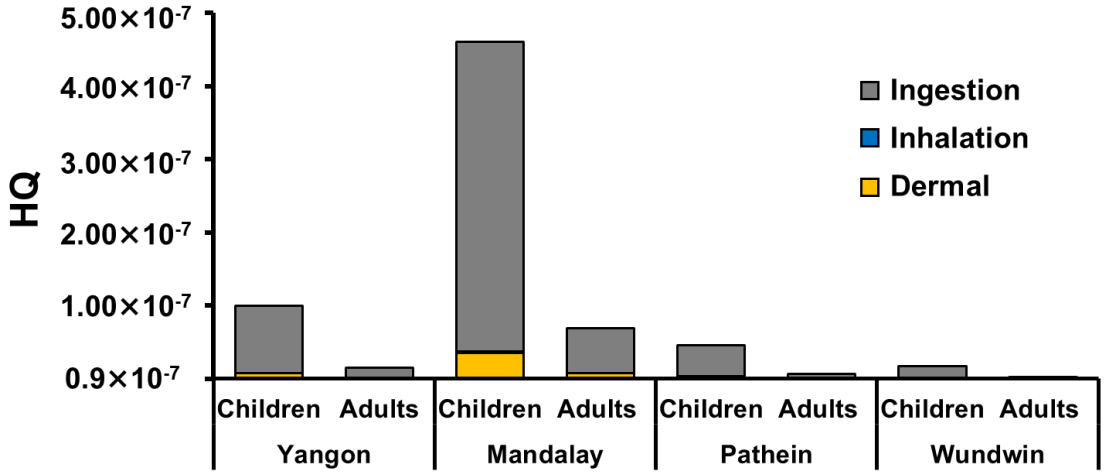

Figure 4.1. Hazard quotients (HQ) and hazard indices (HI) of metals in road dust from urban and suburban areas in Myanmar

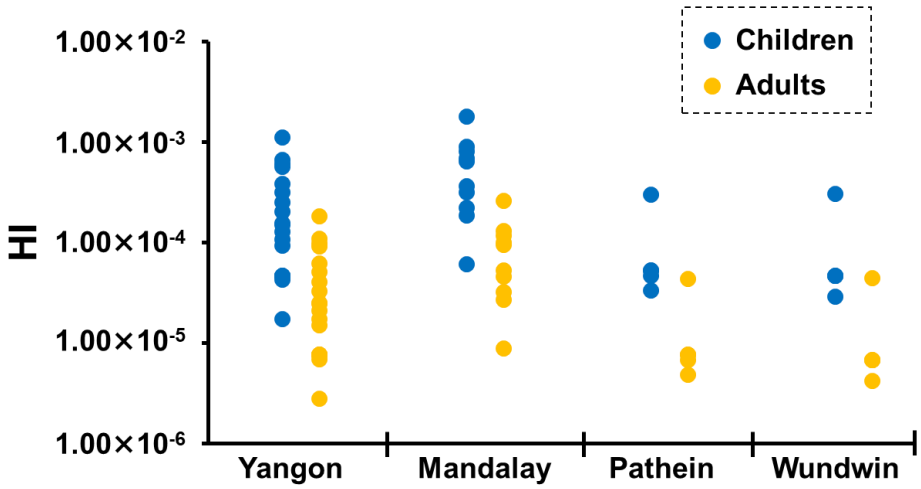

Figure 4.2. Hazard indices (HI) of metals in road dust from urban and suburban areas in Myanmar. Red circle means over 1 of HI.

The relationships between HI for Hg exposure through road dust and population from Myanmar and other countries (Cong Men, Yifan Wang, 2021b; Harb et al., 2015b; Kara, 2020b; Lima et al., 2023a; Zgłobicki & Telecka, 2021b) were significantly positive for children and adults (Figure 4.3).

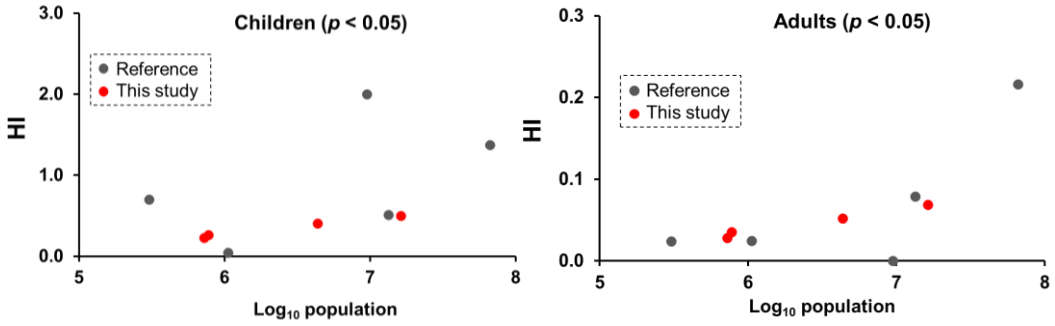

Figure 4.3. Relationship between population and HI in road dust from Myanmar (red circle) and other countries (black circle) (Cong Men, Yifan Wang, 2021b; Harb et al., 2015b; Kara, 2020b; Lima et al., 2023a; Zgłobicki & Telecka, 2021b) for children and adults.

These results indicated that increases in Hg concentrations with population density could introduce higher health risk to humans. Because Myanmar population is increasing, potential human health risk associated dust exposure may be considered in future.

4. Conclusions

Human health risks of Hg exposure from road dust are below the Hazard Index (HI). Therfore, the study suggest that Hg exposure is not expected to pose a significant risk to human health. However, it's important to note that this conclusion is based on the specific data and analysis available up to the point of the study. Road dust composition can vary depending on factors such as location, traffic volume, and industrial activities nearby. Therefore, ongoing monitoring and assessment are essential to ensure that the health risks remain below the HI threshold, especially if conditions change over time.

Additionally, while the overall HI may be below one, it's still important to consider the potential health effects of specific contaminants found in road dust, especially for vulnerable populations such as children, adults, or individuals with specific health conditions.

Chapter VI

General Conclusion

Summary

The study assessed and identified Hg pollution in the ASGM areas of Myanmar and several other relevant Southeast Asian countries. Research should continue to focus on the current situation of ASGM activities in the studied countries and other parts of the world where ASGM activities are permitted because Hg is released by ASGM areas. The study aims to contribute to further research activities, such as health inspections and Hg management in ASGM areas because Hg is still used in these activities. For example, Myanmar has not yet established a national Hg inventory, and its research activities remain limited. Additionally, Myanmar is not yet a part of the Minamata Convention. According to these reviewed studies, it is evident that Hg continues to cause contamination in the vicinity of ASGM areas, including nearby residential areas.

Furthermore, this study also highlights that elevated levels of Hg and other metals were observed in road dust and sediment in urban areas of Yangon and Mandalay. The sources were estimated to include vehicles, municipal waste, and industrial emissions. Urban pollution is significant, but the impact on human health is generally less considered. However, Hg contamination in sediment reveals a moderate ecological risk in urban areas of Myanmar, particularly in Mandalay.

Therefore, regular human epidemiological assessments of Hg-related diseases should be undertaken not only in ASGM areas but also in areas related to Hg sources. Hg-contaminated areas should be controlled through reasonable regulations, policies, and frameworks. In addition, innovative Hg-free processing technologies and alternative economies should be introduced to support ASGM communities in reducing Hg emissions. Consequently, raising awareness of Hg-related problems can effectively reduce Hg pollution in Myanmar.

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