Mercury Pollution in River Nile State, Sudan: Evaluating Process Efficiency and Health Risks in Artisanal Small-Scale Gold Mining (ASGM)

スーダン・ナイル川州における水銀汚染: 自主小規模金採掘（ASGM）のプロセス効率と健康リスクの評価

Abstract:

Mercury is an extremely hazardous element that occurs naturally in the environment. It is a non-essential metal in the human body, and its compounds have numerous negative effects on both the environment and human health. These effects include damage to the lungs, kidneys, skin, eyes, and neurological, immunological, and digestive systems. Additionally, mercury significantly impacts a child's development during pregnancy and early life. Artisanal and small-scale gold mining (ASGM) is a significant anthropogenic source of mercury emissions, posing serious threats to both the environment and public health.

This thesis provides comprehensive insights into the extent of contamination and associated hazards by investigating mercury pollution in ASGM areas, with a specific focus on the Alabediah Mining Market, Abu Hamad Mining Market, and the Darmali area—all located within River Nile State, Sudan. The study specifically sought to:

1. Conduct a mercury mass balance by assessing mercury losses at various stages of the amalgamation process until the creation of dore, allowing for evaluation of the input, recovery, and losses of mercury in the most widely used amalgamation mill in Sudan: the wet pan mill.

2. Apply US EPA (United States Environmental Protection Agency) risk assessment methods to evaluate health risks from contaminated soil and water samples in Formal ASGM areas of Sudan, specifically the Abu Hamad Mining Market.

3. Utilize soil and water samples from diverse land uses to assess the human health hazards in the informal ASGM region, Darmali area, and neighboring villages using US EPA risk models.

Important insights were obtained from the mercury mass balance study during the amalgamation process. It was revealed that at different phases, 94.19% of the mercury added to the amalgamation process could be recovered. However, the residual portion is released into the environment either as tailings or into the air following the burning of amalgam. The amount of mercury released into the atmosphere varied, even though the collected mercury percentage remained constant at 94%. The quantity of gold recovered during the process exhibited a strong correlation with this variation. Since gold has a strong affinity for mercury and the weight of the amalgam is directly related to the amount of gold present, this relationship is logical. Consequently, as the amount of gold recovered increases, mercury emissions into the atmosphere also increase. This illustrates the impact of the proportion of recovered gold on the proportion of mercury released during the amalgamation process. In general, lower mercury percentages in mining tailings are associated with higher gold recovery rates. The current amalgamation practices, in terms of mercury input, recovery, and losses in ASGM operations, are more effective compared to previous amalgamation practices. Additionally, conducting a comparison analysis with international studies has improved our understanding of mercury dynamics in

ASGM contexts, shedding light on the unique characteristics of the amalgamation methods in Sudan. This study is significant because it challenges prior empirical assumptions by providing accurate data on the mercury-to-gold ratios used in ASGM operations. Given that they offer a more accurate understanding of mercury usage and emissions in ASGM activities, these findings hold paramount significance for the scientific community. The study also highlights the urgent need for better safety precautions, especially while burning amalgam. It is highly recommended that retorts be used throughout this procedure to reduce the amount of mercury vapor that people in the ASGM areas are exposed to and to lessen environmental damage. This underscores the importance of implementing feasible solutions to safeguard the environment and public health in ASGM communities.

In the formal ASGM areas in Sudan, mercury levels were found to be elevated in all soil and water samples taken from the ASGM Mining Market. The samples taken from areas where amalgam was burned had the highest contents of mercury—34.8 mg/kg in soil and 3.26 μg/L in water. Although concentrations dropped with distance, soil samples close to burning sites (34.8 mg/kg) still had higher concentrations than those close to tailings (19.0 mg/kg). All water samples collected inside the ASGM area (n = 3) surpassed Japan's water quality limit for total mercury, which is 0.5 μg/L. However, the water samples taken outside of the ASGM area fell below this threshold. Since all of the water utilized in the area comes from the Nile, it is important to note that this indicates the Nile River water is uncontaminated. Additionally, levels greater than 1 mg/kg were found in soil samples from the ASGM region. Hazard quotients indicate that breathing mercury vapor from the soil is the primary exposure pathway; adult Hazard Index values near amalgam burning sites may reach 5.34, while child Hazard Index values can reach 33.4. Most water samples pose low risk, with the probable exception of the sample next to the amalgam burning site, where children could be exposed to ingestible risks (HI = 1.74). Ingesting soil and water contaminated with mercury increases the risk significantly. However, inhalation of suspended particles is regarded as essentially negligible compared to other exposure routes. These findings demonstrate the crucial need to establish eco-friendly practices and countermeasures to reduce mercury emissions and protect ASGM populations.

Following the amalgamation process, the reprocessing of amalgamation tailings poses serious environmental and human health risks. This issue is magnified because artisanal miners carry out this process informally in the ASGM sector in Sudan. Populations in the Darmali area and its surroundings are exposed to reprocessed amalgamation tailings, which are scattered across agricultural and residential areas. This exposure is particularly concerning because the affected population includes a wider range of community groups—such as elderly people, pregnant women, and other vulnerable individuals—unlike in formal ASGM settings, where the exposed population primarily consists of adult males. However, the tailings produced in the Darmali area contain lower mercury content (5.1 mg/kg – 12.6 mg/kg) compared to those found in formal ASGM settings, where the average mercury content is 19 mg/kg. This study assessed the mercury content in soil and tailings samples, as well as in tap and groundwater, to evaluate human health risks from ASGM activities and to assess contamination levels within the study area. Soil and water samples were collected from various locations, including agricultural, residential, and tailings sites, as well as groundwater and tap water from the Nile. Besides mercury analysis, contamination levels were assessed using geo-accumulation index analysis, which

revealed extreme pollution levels in areas with tailings and moderate pollution levels in agricultural and residential areas. Hazard quotients were applied to assess health risks, with inhalation of mercury vapor identified as the primary exposure route, consistent with findings in formal settings. The results indicated that tailings pose significant health risks, particularly for children, while water samples and soil from agricultural and residential areas did not pose significant risks. These findings underscore the urgent need for authorities and local communities to address mercury contamination by removing and treating tailings from affected areas to mitigate health risks.