Mercury Contamination in Nam Son Landfill, Hanoi, Vietnam: Environmental and Human Health Risks

ベトナム、ハノイのナムソン埋立地における水銀汚染：環境と人間の健康へのリスク

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The degree of Doctor of Philosophy

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September 2024

ABSTRACT

Mercury is one of the top ten chemicals or groups of chemicals of major public health concern, its emissions pose a global environmental pollution problem. In the natural environment, Hg can participate in the biochemical cycle, it can be converted to methylmercury - the unique form of Hg by converting the original soil environment from aerobic to anaerobic and engaging with microorganisms. Hg cause problems such as kidney and nerve damage, sleep disturbances, hearing loss, impaired reproductive function, and heart issues. Hg is classified by the US Environmental Protection Agency (EPA) as a group D carcinogen, and methyl mercury is classified as a group C carcinogen. However, Hg is still used in the manufacture of skin care products and consumer goods such as thermometers, lamps, batteries, watches, switches. After these products are no longer in use, they still contain a certain amount of Hg and can disperse into the environment if not properly recovered.

Landfills are concerning due to pollution caused by the classification, collection, and treatment of waste, especially in developing countries like Vietnam. Landfills have the potential to contribute to Hg pollution, due to the burial of waste containing Hg. Thus, in this study, we investigated the potential risks of Hg to humans and the entire ecosystem using soil and rice samples sourced from paddy fields located near the Nam Son landfill area in Soc Son, Hanoi, Vietnam.

Specifically, Chapter 1 discuss about the general introduction and literature review. Chapter 2: In this study, we assessed the levels of Hg in the paddy soil around

the Nam Son landfill, during both rainy (September 2021) and dry (January 2022) seasons. The concentration of Hg was in the range of 20.5 to 79.7 μg/kg dry w.t. in Bac Son and Nam Son, and 16.6 μg/kg dry w.t. at a higher reference site. In most of the samples, the rainy season showed higher Hg concentrations than the dry season. Soil samples taken closer to the landfill exhibited higher levels of Hg contamination compared to those in more distant paddy areas, suggesting a decreasing trend of Hg concentration as one moves away from the pollution source. Additionally, Hg concentration was found to decrease vertically from the surface, with the higher value observed in the surface layer (0 – 5 cm), and the lower in the bottom layer (20 – 25 cm). The geo-accumulation index showed that all the sampling points were moderately to heavily polluted, indicating that Hg was lost from the waste source in the landfill. This study provides valuable insights into the spatial and vertical distribution of Hg pollution in the topsoil and highlights the importance of managing and assessing the risks of Hg-containing waste. The Hg concentrations in the paddy soil from Nam Son landfill were positively correlated with soil organic matter (SOM), but no correlated with pH.

Chapter 3: This study evaluated the mercury contamination in rice plants, which are typical foods cultivated in the Red River Delta. Mercury (Hg) accumulation in rice is a health concern due to the consumption of rice as the staple food. This study evaluated the mercury contamination in rice plants, which are typical foods cultivated in the Red River Delta. During the harvest season, rice samples were collected and separated into husk and brown rice, together with polished white rice and bran rice from mill shop. For brown rice, the Hg concentration ranges from 7.18 ± 0.73 to 16.32 ± 2.57 μg/kg.

Additionally, brown rice samples near landfill or highway tend to have higher Hg concentrations than sites farther away. Hazard quotient (**HQ**) was used to measure the health risk of Hg in this study. HQ values of male and female all were less than one, indicating that consuming rice from Nam Son and Bac Son might not cause potential human health risk of Hg exposure.

Chapter 4: This study investigated the hair Hg concentrations and assessed the Hg exposure through rice consumption for local residents around the Nam Son landfill area. Thus, 16 human hair samples, along with questionnaires, were collected to assess Hg exposure and human health risks to residents living near the Nam Son landfill. Additionally, the study aimed to investigate their exposure to Hg through rice consumption and significant predictors of hair Hg levels, such as age groups, smoking habits, occupation, through questionnaires. The results showed that the mean of Hg concentration in hair was 0.88 ± 0.05 mg/kg lower than the reference level (1.0 mg/kg) recommended by the United States Environmental Protection Agency (US EPA), indicating that residents in this area were exposed to low levels of Hg. There was no significant difference in the accumulation of Hg in hair between different age groups, smoking habits, and rice consumption. However, there was a significant difference between landfill workers and non-landfill workers, suggesting that landfill activities directly affect human mercury exposure.

Keywords: Vietnam, Nam Son landfill, mercury, soil, rice, hair, paddy field, HQ

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Acknowledgement

First of all, I would like to express my gratitude to the Kumamoto Prefecture Government and Prefectural University of Kumamoto in Japan. This study would not be possible without International Postgraduate Scholarship for Mercury. It provided a great opportunity for me to not only study mercury in depth, but also learn about the beauty of Japanese culture and traditions. The knowledge I have gained here is a valuable experience that I will remember forever.

I would like to thank my supervisor, Professor Yasuhiro ISHIBASHI, and my co-supervisors, Professor Koji ARIZONO and Professor Jun KOBAYASHI for their dedicated guidance, valuable comments, and encouragement. I am honored to be your student. I sincerely appreciate to all the professors, associate professors, staffs of the Faculty of Environmental and Symbiotic Sciences for their invaluable support and contributions.

I would like to express my sincere thanks to my friends, especially the members of the Ishibashi laboratory and the Mercury students. We have spent memorable times together, studying, researching and helping each other. I have learned many valuable things from you. Although each of us has a new destination, I hope to continue to cooperate with you in the future.

Finally, to my beloved family, my deepest gratitude. My parents and brothers have been my strong spiritual support, always sharing, and encouraging me while I study in Japan.

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Chapter 1: General Introduction

1.1. Background

Mercury (Hg) is known as a metal that exists in liquid form at standard condition of temperature and pressure (Clarkson & Clarkson, 1997). Hg can come from natural sources such as volcanic eruptions, forest fires, cinnabar or anthropogenic sources such as metal smelting, coal production, chemical synthesis and use, and waste disposal (Tchounwou et al., 2003), undergoing the process of evaporation and deposition of Hg forming the global Hg cycle (Beal et al., 2014; Dastoor & Larocque, 2004). In the natural, Hg exist in the three form: elemental mercury or quicksilver (metallic mercury and vapor mercury, Hg^0), inorganic mercury (Hg^+ and Hg^{2+}), and organic mercury (methylmercury and ethyl mercury) (Bhan & Sarkar, 2005).

The mechanism of Hg toxicity involves protein precipitation and inhibition, interference with DNA synthesis (Carvalho et al., 2008), inhibition of enzymes and being corrosive (Broussard et al., n.d.). Exposure to Hg or its compounds may cause adverse health effects, and the severity of such toxic effects depend on the chemical form, the dose, frequency of exposure, duration of exposure, and route of exposure. Specifically, Hg^0 is widely distributed and accumulated within the body tissues, but the brain is the major site for its toxicity. The major route of exposure of Hg^0 is inhalation due to its high volatility even at room temperature, hence the atmosphere is the major exposure source contributing to about 70 - 85 % absorption rate of Hg^0. InHg, which is majorly available as salt of either Hg (I) or (II) compounds, cause toxicity to the renal, cardiovascular, reproductive, hepatic and gastrointestinal tract systems. Organic Hg compounds include both alkyl organic mercurial (OMs) such as methylmercury (MeHg), dimethyl mercury, ethyl mercury, etc. and aryl OMs., phenylmercury. The OMs are highly lipid soluble or lipophilic and have high affinity for SH groups on cysteine, glutathione and other biomolecules. Hence, OMs are mainly neurotoxic but can also be teratogenic, nephrotoxic, mutagenic, genotoxic, hepatotoxic as well as cause haematological and immunological effects.

In recent years, the issue of Hg pollution caused by anthropogenic sources has gained significant attention, in addition to Hg emissions from natural sources. Globally, artisanal and small-scale gold mining (ASGM) is identified as the largest contributor (37 %) to Hg emission, followed by vinyl chloride monomer (VCM) production, measuring and control equipment, and dental applications（*Global Mercury Supply, Trade and Demand*, n.d.）. However, in Vietnam, the primary sources of mercury emissions are associated with the use and disposal of Hg-containing products, waste incineration, waste burial, and wastewater treatment (Hanoi, 2017). This data is closely related to the current situation in Vietnam where harmful waste, including waste containing Hg, they were collected together, transported and buried directly in the landfill. These activities release a large amount of Hg into the surrounding environment through the process of landfilling or burning waste.

The Nam Son landfill is the biggest landfill in the north Vietnam, Nam Son landfill is located in Red River Delta and approximately 45 km from central Hanoi. Nam Son waste treatment complex has a total area of 83.5 hectares, including a wastewater treatment plant, a waste power plant and closed and operating landfills. The landfill was initially designed to handle about 2000 tons of waste per day in 1999 (phase 1), the landfill is currently receiving over 5000 tons/day due to the consistent exceeding of its capacity (Giang et al., 2018), the daily leachate volume of 2500 m^3/day, exceeds the wastewater treatment plant's work capacity of 2150 m^3/day [21]. The process of transporting, burying and treating waste can release toxic substances including organic compounds (Andrew et al., 2011) and heavy metals (Hoai et al., 2021; Giang et al., 2018) into the environment around the landfill. However, agricultural and residential activities are still taking place around the landfill. Some fields and fish ponds of local people are only 200 m away from the landfill, leading to agricultural products here being contaminated with organic substances or heavy metals, including Hg, which pose health risks to people living in this area. Therefore, the objective of this study is determining the mercury contamination of environmental and food, the distribution of mercury in soil and the implication to the ecological and human health around Nam Son landfill, Hanoi, Vietnam. The specific objectives were to:

a) Assessment the mercury contamination in environmental and food in resident around landfill area.

b) Risk characterization of mercury consumption pattern from environmental and food in general population.

c) Hair mercury concentration related with rice consumption and factors affected on it.

These three specific objectives constituted the chapters 2, 3, and 4 of this study, respectively.

Chapter 2: Spatial and Seasonal Patterns of Mercury Accumulation in Paddy Soil around Nam Son Landfill, Hanoi, Vietnam

Citation:

Nguyen Thi Quynh, Huiho Jeong, Ahmed Elwaleed, Tetsuro Agusa, Koji Arizono and Yasuhiro Ishibashi (2024). Spatial and seasonal patterns of mercury accumulation in rice paddy soil around Nam Son landfill, Hanoi, Vietnam. *Soil Syst.* **2024**, *8*(1), 30; https://doi.org/10.3390/soilsystems8010030

2.1. Introduction

Mercury (Hg) emissions are an environmental pollution challenge globally, as it is a transboundary pollutant (Dziok et al., 2020). Unique among heavy metals, Hg exists in gaseous and liquid states under ambient conditions (Luo et al., 2021), allowing it to persist in the environment and undergo complex distribution processes (Xu et al., 2020). In the presence of anaerobic soil environments and microorganisms, Hg can transform into methylmercury (MeHg) through biochemical cycling (Mergler et al., 2007). The US Environmental Protection Agency (EPA) classifies Hg as a Group D carcinogen, while MeHg is classified as a Group C carcinogen, with detrimental effects primarily observed in the central nervous symptoms and kidneys (Cariccio et al., 2019; Fernandes Azevedo et al., 2012). Individuals exposed to these substances may experience various symptoms, including language impairment, renal damage, tremors, sensory disturbance, unbalanced rigidity, and ataxia (Saldaña-Villanueva et al., 2022). Consequently, on October 10, 2013, the United Nations Environment Program (UNEP) adopted the Minamata Convention on Mercury ("Mercury Convention"), to outline regulations and measures aimed at reducing global mercury emissions (S. Liu et al., 2021).

In recent years, the issue of Hg pollution caused by anthropogenic sources has gained significant attention, in addition to Hg emissions from natural sources. Globally, artisanal and small-scale gold mining (ASGM) is identified as the largest contributor to Hg emission, followed by vinyl chloride monomer (VCM) production, measuring and control equipment, and dental applications (*Global Mercury Supply, Trade and Demand*, n.d.). However, in Vietnam, the primary sources of mercury emissions are associated with the use and disposal of Hg-containing products, waste incineration, waste burial, and wastewater treatment (Hanoi, 2017). According to data on Vietnam's sanitary landfills, there are 98 waste landfills operating nationwide, but in which, only 16 are considered sanitary landfills. Approximately 85 % of urban and older towns still rely on unhygienic landfills where waste is not properly separated, leading to the burial of hazardous waste, including Hg-containing waste. The main contributing factor to this situation is the disposal of solid waste containing mercury, such as skin care products (Hamann et al., 2014), thermometers, lamps, batteries, watches, and switches (Horowitz et al., 2014) enters landfills for treatment via the waste stream (Zhu et al., 2013a). As a result, landfills in Vietnam have become potential sources of mercury pollution.

For extended periods of time, several studies investigated the transfer and accumulation of Hg contamination originating from landfills. For instance, Tao et al., 2018 (Tao et al., 2018) examined the Hg and MeHg concentrations in soil at two landfill Laogang and Jiangcunggou in China, and found the highest concentrations to be 0.169 ± 0.12 µg/g and 0.107 ± 0.08 ng/g, respectively. In Seoul, South Korea, Kim et al., 2001 (K.-H. Kim et al., 2001) measured atmospheric Hg levels at the Nan-Ji-Do landfill, ranging from 0.73 to 9.47 ng/m^3. Hoai et al., 2021 (Hoai et al., 2021) conducted a study Nam Son landfill and evaluated heavy metal concentrations in leachate samples found Hg concentrations to be 0.0061 mg/L and 0.006 mg/L in March 2017 and March 2018, respectively, this concentration is exceeding QCVN 40:2011/BTNMT National Technical Regulation on Industrial Wastewater. This landfill serves Hanoi city's waste treatment needs, but the overloaded treatment facilities increasing the potential for environmental pollution (Hoai et al., 2021). Such elevated levels of Hg in leachate raise concerns about its release into the environment through leachate (Jabłońska-Trypuć et al., 2021) or dry and wet deposition (Sakata & Marumoto, 2005). Hence, it remains crucial to identify, characterize, and accurately estimating Hg emissions from landfill sources. This study focuses on Nam Son landfill, the largest landfill in the northern Vietnam, where no clear data on Hg concentration in the agricultural soil surrounding the landfill currently exists. The aim of this study is to investigate Hg concentration in soil layer (0 – 5 and 20 – 25 cm) and determine the factors that affecting mercury distribution, including geochemical properties such as distance from landfill, weather conditions, and wind direction.

2.2. Materials and Methods

2.2.1. Sampling Sites

Sampling was conducted at the Nam Son landfill (Soc Son, Hanoi, 21◦20′2″ N, 105◦50′9″ E), situated in the Red River Delta (RRD), approximately 45 km north of Central Hanoi, Vietnam (**Figure 2.1**). The area experiences a subtropical humid monsoon climate with an average annual rainfall of 1670 mm and an annual mean air humidity is 84 % (Giang et al., 2018). The Nam Son landfill is located in the north of Vietnam; the climate here is distinctive, with cold winters and hot and humid summers. Northern Vietnam has a rainy season stretching from May to October and a dry season from November to April. As for the monsoon, from November to April, there is an active winter wind blowing in the northeast direction, and from May to October, there is an active summer monsoon blowing in the southwest and southeast directions. The Nam

Son landfill is part of the Nam Son Waste Treatment Complex, originally covering an area of 83.5 hectares, with the landfill area occupying 53.49 hectares. The Nam Son landfill was initially designed to handle about 2000 tons of waste per day in 1999 (phase 1), the landfill is currently receiving over 5000 tons/day due to the consistent exceeding of its capacity (Giang et al., 2018). Organic waste constitutes the largest portion of waste at Nam Son landfill (51.9%), along with some of inorganic waste such as plastic and nylon (3.0%), paper and carton (2.7%), leather and rubber (1.3%), metals (0.9%), glass (0.5%), inert matter (38.0%) and other materials (1.7%) (The World Bank, 2018). Besides the landfill, the Nam Son Waste Treatment Complex includes a newly operational waste power plant since July 2022 and a wastewater treatment plant. However, the daily leachate volume of 2500 m^3/day, exceeds the wastewater treatment plant's work capacity of 2150 m^3/day (URENCO, 2018). As a result, the degradation of geotextile layer, differences in water flow pressures, and the fissured rock environment create favorable conditions for the pollutants from landfilled wastes to leak into surface water and groundwater (Giang et al., 2018), causing environmental issues such as foul odors, ecological damage, and environment degradation.

An additional reference sampling site (Ref) was collected in Minh Phu, Soc Son, Hanoi, approximately 9 km away from the Nam Son landfill, in January 2023. This control site was chosen due to its distance from highways, factories, cities and landfills.

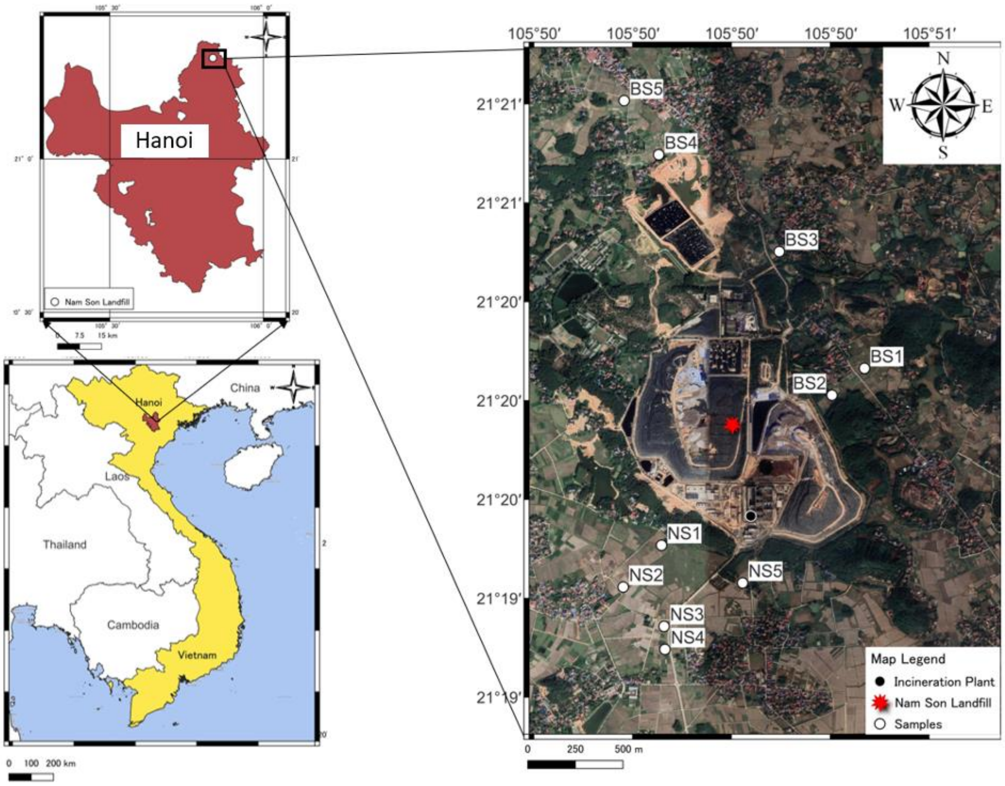


Figure 2.1. Map of sampling sites in Nam Son, Soc Son, Hanoi.

2.2.2. Sample Collection

The field sampling campaigns for soil contamination around the Nam Son landfill were conducted in September 2021, during the rainy season, and January 2022, during the dry season. A total of 20 soil samples were collected, including duplicates, from two communes, Nam Son (NS1–NS5) and Bac Son (BS1–BS5), situated around the landfill. The sampling locations covered varying distances from the landfill, with some towards the south in the Nam Son commune and others towards the north in the Bac Son commune. The soil sampled is rice paddy soil, the depth of 25 cm from the surface is the topsoil layer that directly affects rice quality. Furthermore, we divided it into surface layer (0 - 5 cm) and bottom layer (20 - 25 cm) because of the soil properties and organic matter composition of these two soil layers are different, which can lead to differences in Hg concentration. Each soil sample was labeled, stored in a polyethylene ziplock bags and kept at 4 ^{o}C for transportation to the laboratory. Soil samples were dried at room temperature (Kodamatani et al., 2017). Subsequently, the dried samples were ground using a porcelain mortar and pestle and sifted through a 150 μm mesh size sieve to obtain finer particles. All the soil samples were stored in a – 4 ^{o}C freezer until they were ready for analysis.

2.2.3. Sample Analysis

a) Hg analysis

The Hg concentration in the soil samples was analyzed by direct thermal decomposition mercury analyzer (MA-3000, Nippon Instruments Corporation, Tokyo, Japan). Approximately 30 mg of each sample was weighed in triplicate and placed into sample boats, which were then loaded into the MA-3000. Calibration curves were generated using standard solutions of Hg^{2+} at concentrations of 10 μg/L, 100 μg/L, and 1000 μg/L for both low and high calibration curves.

b) pH analysis

Soil pH measurements were performed using a pH-meter (AS 800, AS ONE Corporation, Osaka, Japan) in triplicate. Approximately 2 g of each sample was weighed into 50 mL polypropylene tube with crew caps. Then, 50 mL of ultrapure water (Milli-

Q® Millipore, USA) was added to the tube, and the mixture was shaken for 5 minutes at a speed 250 rpm (Addai-Arhin et al., 2022).

c) Determination of SOM in soil sample

The soil organic material (SOM) content was estimated by measuring the percent loss on ignition, as described by Lewis et al., 2014 (Lewis et al., 2014). Approximately 1 g of soil sample was weighed into ceramic crucible and subjected to burning at 550 ° C for 4 h. Each sample was repeated three times. The percentage loss in weight (SOM) was calculated using the equation 1:

$$\mathbf{(W1 - W2)/\ (W1 \times 100\%) = SOM\ (\%)} \quad (1)$$

where

W1: is the weight of the soil sample before burning (g);

W2: is the weight of the soil sample after burning (g).

2.2.4. Quality Assurance (QA) and Quality Control (QC)

During the laboratory analysis, stringent measures were taken to ensure a contamination-free environment. An ultra-clean bench was utilized, and all the water used had a high purity level of 18.2 MΩ·cm at 25 ◦C (Millipore, Burlington, MA, USA). Reagents of guaranteed purity (GR) were selected to avoid any contamination or ultra-low blanks.

To establish baseline measurements and guarantee the accuracy of the Hg analyses, additive B was employed as a blank. A comprehensive quality assurance and quality control program was implemented, incorporating method blanks, certified reference materials (CRM), specifically ERM-CC580 (Institute of Reference Materials Measurements, Belgium) for Hg, and triplicated samples. The obtained results from this method demonstrated excellent agreement with the reference values, with a mean value of 132 ± 3 mg/kg. The recovery rates for the certified reference materials ranged from 96.9% to 101.7% for the Hg analysis, and the relative standard deviations were consistently < 5% for Hg.

2.2.5. Geo-Accumulation Index

The degree of soil contamination by Hg was assessed using the geo-accumulation index, calculated according to Equation 2 proposed by Muller at al., 1969 (Muller., 1969):

$$\mathbf{I_{geo} = log2\ C_{Hg}/1.5 \times B_{Hg}}\ (2)$$

where

I_{geo}: geo-accumulation index for Hg;

C_{Hg}: Hg concentration in the soil (the average Hg concentration in each soil sample);

B_{Hg}: local Hg background (the Hg concentration (7.47 μg/kg dry w.t.) of the bottom layer from the reference sampling point (Bolaños-Álvarez et al., 2016));

1.5: the factor used to correct lithogenic effects.

The I_{geo} was divided into seven classes and was shown specifically in **Table 2.1**.

Table 2.1. The classes of I_{geo}.

Class 0	$I_{geo} \leq 0$	Unpolluted
Class 1	$0 < I_{geo} \leq 1$	Unpolluted to moderately polluted

Class 2	$1< I_{geo} \leq 2$	Moderately polluted
Class 3	$2 < I_{geo} \leq 3$	Moderately to heavily polluted
Class 4	$3 < I_{geo} \leq 4$	Heavily polluted
Class 5	$4 < I_{geo} \leq 5$	Heavily to extremely polluted
Class 6	$5 < I_{geo}$	Extremely polluted

2.2.6. Statistical Analysis

The statistical analysis was conducted using IBM SPSS Statistics SPSS 26.0 software from IBM Corporation, New York, NY, USA. The Shapiro–Wilk test was used to assess whether the data might be well-described by a normal distribution. The Durbin–Watson statistic was used to diagnose the residuals of the linear regression of soil samples in both seasons, there is no autocorrelation. The linear regression analysis was applied between the Hg concentration and SOM and pH, and the significance of the coefficient of determination (R^2) was confirmed using OriginLab 2023b (version 10.05) software. Then, Pearson's analysis was applied to assess the correlation significance of the Hg concentration in the paddy soil relative to the distance to the landfill, between the dry season and the rainy season, and between the two layers (0–5 cm and 20–25 cm). Significance levels were determined based on p values, where values lower than 0.05 were considered statistically significant.

2.3. Results and Discussion

2.3.1. Hg Concentration in Soil

The concentration of Hg in the soil surrounding the Nam Son landfill area is shown in **Figure 2.2**. During the rainy season, Hg concentration ranged from 20.5 ± 1.22

to 47.7 ± 3.60 µg/kg dry w.t. in the Nam Son commune and 29.6±1.19 to 79.7±1.92 µg/kg dryw.t. in the Bac Son commune. In the dry season, the range was 26.0 ± 2.77 to 58.5 ± 3.52 µg/kg dry w.t. in the Nam Son commune and 27.5 ± 2.52 to 73.4 ± 2.51 µg/kg dry w.t. in the Bac Son commune. The average value of all the samples was 44.1 ± 2.20 µg/kg dry w.t., significantly higher than the reference sample concentration in the RRD (16.6 ± 1.48 µg/kg dry w.t.). However, it is important to note that the concentrations of Hg in all soil samples remained below the standard Hg level for safe agriculture soil (12,000 µg/kg), as recommended by the Vietnamese government (QCVN 03:2023/BTNMT, 2023).

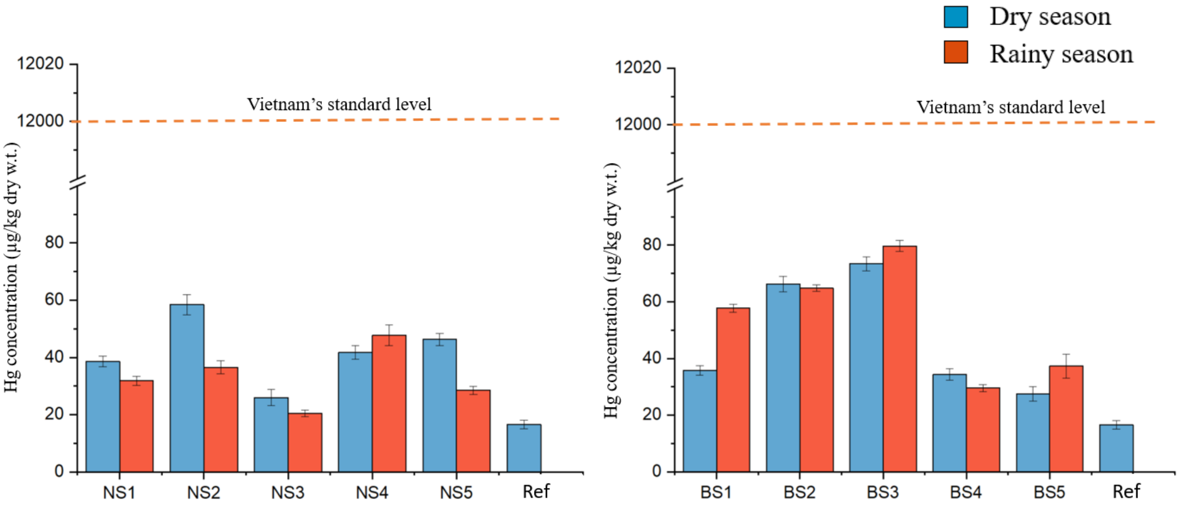


Figure 2.2. Hg concentration in both soil sample layers in the Nam Son and Bac Son communes.

The highest Hg concentration of 78.9 ± 1.91 μg/kg dry w.t. was found in soil sample BS3 (January 2021), located 300 meters from the landfill and situated across the Lai Son canal, indicating the direct effect of seepage through the landfill deposits (Giang et al., 2018). Conversely, the lowest Hg concentration of 21.3 ± 1.92 μg/kg dry w.t. was observed in soil sample NS3 (September 2021), situated in Nam Son commune. The difference was not statistically significant (p > 0.05) in Hg concentration between dry and rainy season during both Nam Son and Bac Son communes. However, in most of samples, rainy season showed higher Hg concentration than dry season. Research by He et al conducted in the municipal solid waste (MSW) landfill, Nagasaki, Japan also reported the detection of T-Hg concentration in the soils ranged from 0.2270 to 2.9190 mg kg^{-1} dw (median: 1.1410 mg kg^{-1} dw) (He et al., 2018). Besides, research by Wei et al also showed the release of Hg from landfills, the Hg concentration measured in the atmosphere at Shanghai Laogang MSW Landfill was recorded to reach 13.5 - 25.2 ng m^{-3} (Zhu et al., 2013). It indicated that Hg MSW is buried in the landfill, it will be deposited as a long-term pollutant, and can be released into the surrounding air, water, and soil through gas emissions and leachate from landfill.

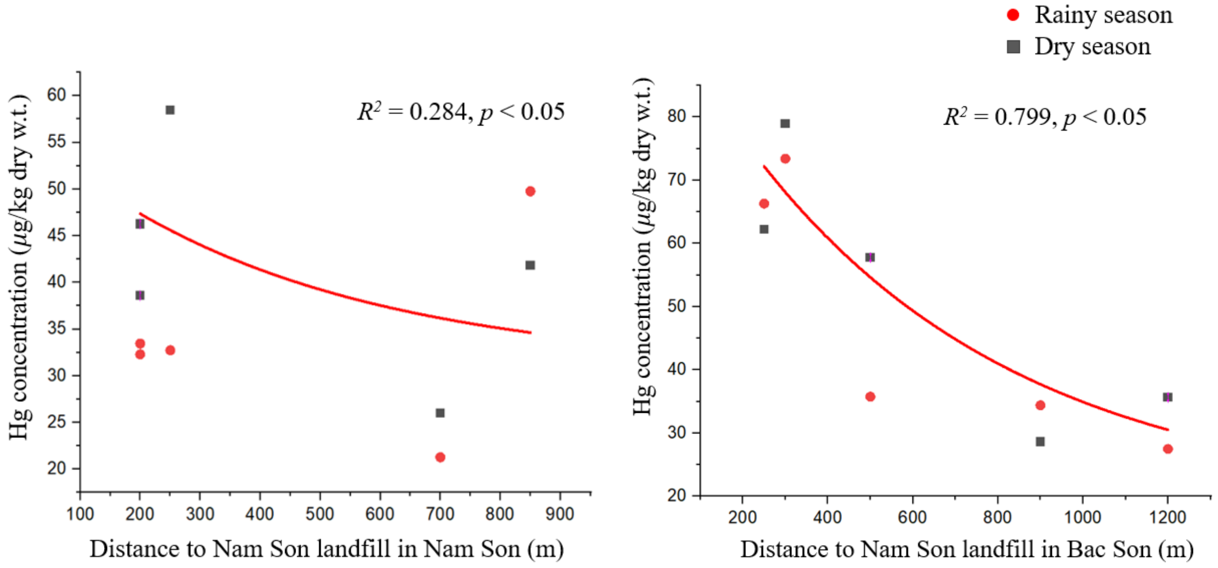


Figure 2.3. Relationship between distance to the Nam Son landfill and Hg concentration in Nam Son and Bac Son.

Figure 2.3 shows the correlation between Hg concentrations in the soil and distance to Nam Son landfill. A lower correlation was found in topsoil Nam Son commune (R^2 =

0.284, $p < 0.05$). The construction of the Nam Son garbage power plant near the south gate of the landfill from 2017 to 2022, along with the transport of construction materials, may have influenced the distribution of Hg in the southern area of the landfill. Conversely, a positive correlation of Hg concentrations in soil was observed in Bac Son ($R^2 = 0.799$, $p < 0.05$), suggesting that Hg concentration tends to decrease with increasing distance from the landfill. This trend is in line with findings reported by Li et al., 2020 (Li et al., 2020), who observed higher Hg concentrations closer to the pollution source of the Guizhou Organic Chemical Plant.

Most of the sampling points (NS1, NS2, NS3, NS5, BS2, BS3, and BS4) showed higher Hg concentrations in January compared to September, which can be attributed to the sampling time aligning with the dry season in the RRD for January and the rainy season for September (Raghavan et al., 2017). During the rainy season, May to October, both irrigation and rainfall wet the soil surface, leading to increased total gaseous Hg emissions from the soil surface (Gabriel et al., 2011). This is consistent with findings by Barletta et al., 2012 (Barletta et al., 2012), who demonstrated that Hg loading in tropical estuaries is largely influence by the rainfall regime.

Besides, the rice cultivation also affects Hg concentration, September is the harvest season, Hg can be absorbed by rice plants (Meng et al., 2014). Meanwhile, in January, when the soil is left idle before the growing season, the amount of Hg accumulated in the soil was higher.

In contrast, NS4 and BS1 exhibited a different pattern, with higher Hg concentration in September compared to January. This difference is attributed to the influence of the

Southwest Monsoon (SWM) on the Nam Son landfill during September, and the active Northeast Monsoon (NEM) during January, 2022 (Loo at el., 2015; Ashfold et al., 2017). Additionally, the southeasterly trade winds (STW) remain dominant and active year-round. Monsoons have been identified as the primary factor controlling the seasonal variation of total gaseous mercury (Chen et al., 2013), affecting the movement of Hg in the atmosphere and leading to changes in the accumulated Hg concentration in the soil.

The spatial and seasonal distribution of Hg concentration in the soil is influenced by various physical factors. Monsoons, precipitation regime and surface water irrigation movement play a significant role in affecting the distribution of Hg. Additionally, Hg depletion with distance is influenced by factors such as soil water retention and mercury adsorption, which are influenced by the organic carbon content, texture, and other soil properties. Soil mixing activities, such as plowing and tillage, also contribute to the spatial variation of Hg concentration in the soil (Morosini et al., 2021).

2.3.2. Vertical Distribution of Hg Concentration

The vertical distribution of Hg concentration is shown in **Table 2.2**. In January 2022, the highest Hg concentration of 92.2 ± 2.55 μg/kg dry w.t. was observed in surface layer at BS3, while the bottom layer of BS3 exhibited lower Hg concentration of 54.6 ± 4.26 μg/kg dry w.t.. This decreasing trend in Hg concentrations with increasing soil depth, was observed at all sampling points during both January and September, including the Ref, NS1, NS2, NS3, NS4, BS1, BS2, BS3, BS4, and BS5. Additionally, there were significant differences ($p < 0.05$) in Hg concentrations between surface and bottom layers during both dry and rainy seasons. These findings indicate that Hg was transported from the surface to the deeper layers, with the surface layer experiencing higher pollutant levels compared to deeper layers (Wang et al., 2021). Similar results have been reported in other studies. Wang et al., 2021 found a significant decreasing trend of Hg concentration from the surface to deeper layers in croplands in northern China. Bolaños-Álvarez et al., 2016 observed a continuous increase in Hg concentrations from 15 cm depth to the surface in riverine sediments in Cuba. The distribution of Hg concentrations decreasing with soil depth may attributed to the deposition of Hg from atmosphere through dry and wet processes into the topsoil (Yu et al., 2018; Braaten et al., 2016; Tomiyasu et al., 2017). The wet deposition is the fall of liquid phase compounds, including major precipitation events such as rainfall and snowfall. The dry deposition is the settling or falling-out of particles due to the influence of gravity, including the deposition of gas-phase compounds and particles too small to be affected by gravity.

Table 2.2. Hg concentration (*μ*g/kg dry w.t.) in surface and bottom layers and bottom layers of soil samples in the Nam Son landfill.

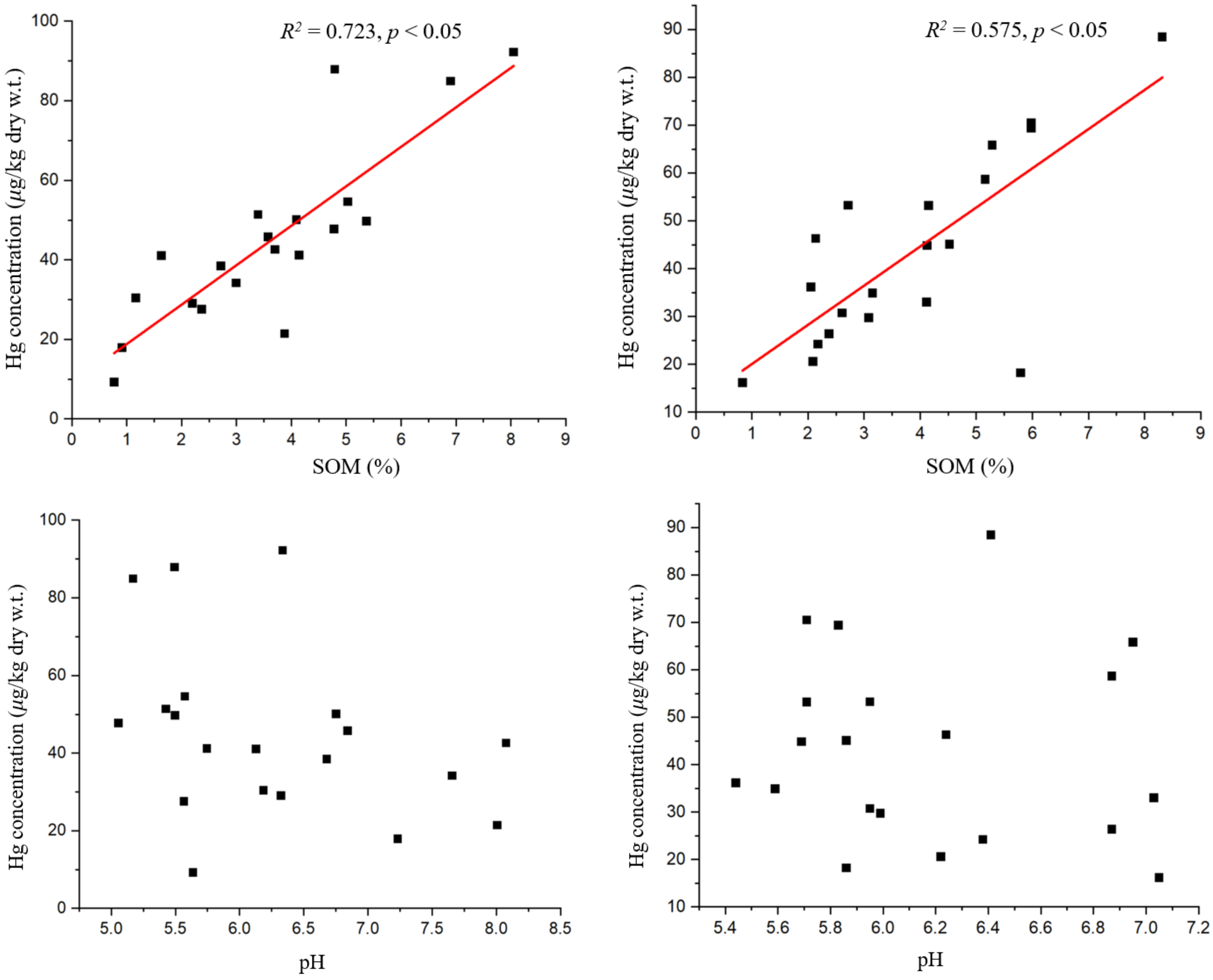
.Sampling point	Hg concentration in Sept, 2021		Hg concentration in Jan, 2022	
	Surface (0 – 5 cm)	Bottom (20 – 25 cm)	Surface (0 – 5 cm)	Bottom (20 – 25 cm)
Ref	-	-	25.8 ± 2.16	7.47 ± 0.80
NS1	34.9 ± 2.04	29.7 ± 2.33	49.7 ± 2.33	27.5 ± 0.71
NS2	44.9 ± 0.43	20.6 ± 0.41	87.9 ± 9.20	29.0 ± 2.08
NS3	26.3 ± 3.31	16.2 ± 0.54	34.2 ± 3.37	17.9 ± 1.19
NS4	53.2 ± 3.87	46.3 ± 3.99	42.6 ± 2.54	41.1 ± 1.88
NS5	30.7 ± 1.99	36.2 ± 0.21	41.1 ± 5.17	51.4 ± 0.22
BS1	70.5 ± 0.96	45.1 ± 2.28	50.1 ± 3.19	21.4 ± 0.79
BS2	65.8 ± 0.94	58.6 ± 1.12	84.9 ± 4.41	47.7 ± 2.59
BS3	88.4 ± 3.52	69.4 ± 0.31	92.2 ± 2.55	54.6 ± 4.26
BS4	33.0 ± 1.50	24.2 ± 0.57	38.4 ± 1.47	30.4 ± 2.08
BS5	53.2 ± 5.42	18.2 ± 1.86	45.8 ± 1.99	9.23 ± 1.80

-: No sample.

Interestingly, the distribution of Hg concentrations at NS5 differed from the general pattern. These sampling points showed noticeably low Hg concentration. In NS5, the higher Hg concentration was observed in the bottom layer during both September and January with value of 36.2 ± 0.21 μg/kg dry w.t. and 51.4 ± 0.22 μg/kg dry w.t., respectively. In RRD, farming activities involve processes like plowing, harrowing, fertilizing, and irrigation with contaminated water from the ditch network. The travel distance of water during irrigation events and the addition of biochar from burning rice straw in fields may also influence the Hg concentration (Liu et al., 2022; Li et al., 2019). It is possible that NS5 is a field where rice straw is not burned, leading to a lager vertical migration of Hg concentration in the soil compared to other fields. These farming activities and irrigation practices could have influenced the Hg concentration at NS5 during sampling time. In conclusion, the vertical distribution of Hg concentration in soil at NS5 appears to be affected by specific farming practices and irrigation, highlighting the complex interplay of factors influencing Hg distribution in the study area.

2.3.3. Effect of pH and SOM on Hg concentration in soils

The SOM and pH analysis were conducted due to their significance as key soil factors that might affect the availability and mobility of Hg in soils (Yang et al., 2007), because the content of Hg adsorbed into soil particles may increase or decrease depending on pH and SOM (Chang et al., 2014). Hg in soil exists in many different forms such as organic mercury (MeHg) or free ionic Hg^{2+}, while if the soil pH is acidic, it will promote Hg to become soluble (Hg^{2+}) and be easily absorbed. SOM has a high affinity for Hg and shows strong binding, and is a positive factor to Hg methylation in soil and thereby increasing Hg bioavailability towards plants (Natasha et al., 2019). Soil pH ranged from 5.05 to 8.08, integrating these results indicated that the agricultural soils in sampling area was slightly acidic. These values were close to neutral pH and typical or the Eutric Fluvisols of RRD. SOM varied from 0.77 to 8.32 %, higher C levels observed at the top layer, could be a result of irrigation using domestic wastewater with high organic matter content (Duc et al., 2007).



Dry season **Rainy season**

Figure 2.4. Relationships between SOM and pH, and Hg concentrations in both soil layers in dry and rainy seasons.

The linear regression analysis conducted for both soil layers showed that there were significant correlations between SOM and Hg concentrations in both dry and rainy season ($R^2 = 0.723$ and 0.575, respectively; $p < 0.05$) (**Figure 4**). The Durbin-Watson test was used to diagnose the residuals of soil samples in both seasons, the results suggest that there was no autocorrelation (d = 2.14 and d = 1.41 in dry and rainy season, respectively). Thus, SOM may play an important role in Hg accumulation. In contrast, soil pH values had no correlations with Hg concentrations in soil ($p > 0.05$) (**Figure 2.4**). This result is consistent with other study (Bortey-Sam et al., 2015) which indicated that pH had minor or no significant effect on the accumulation of metals.

2.3.4. Geo-Accumulation (Igeo) in soil

The I_{geo} index was caculated for each sampling point to assess the contamination level of mercury in the soil. **Figure 2.5** shows the I_{geo} index of Hg in the soil layer at each sampling site in January 2022. For paddy soil around the Nam Son landfill, the I_{geo} values ranged from 1.2 to 2.7, categorizing them as moderately polluted to heavily polluted according to the geo-accumulation index.

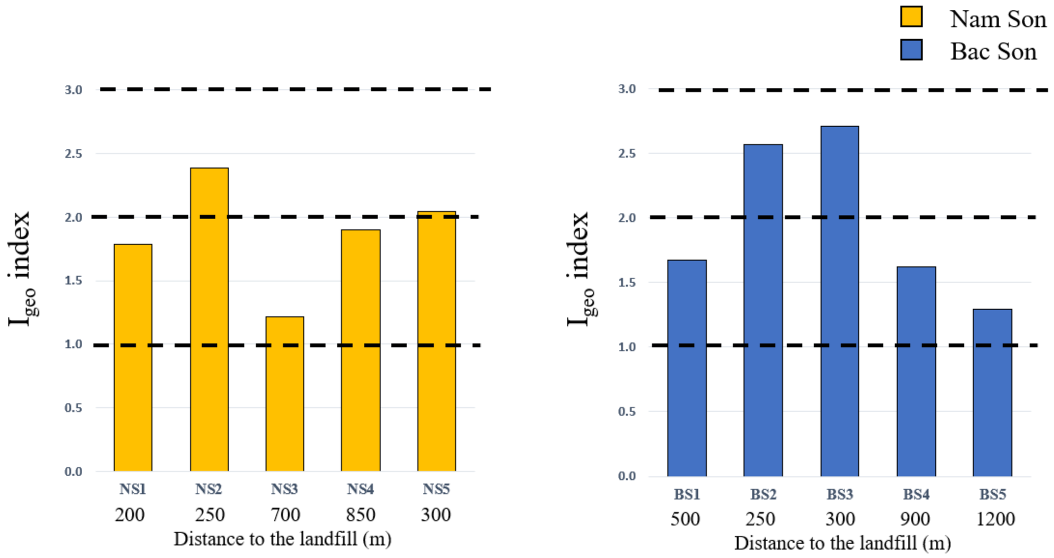


Figure 2.5. I_{geo} (value and class) for each sampling point and distance to the landfill (m) in (a) Nam Son and (b) Bac Son.

The I_{geo} values for sampling sites in Nam Son commune (NS1, NS3, and NS4) and Bac Son commune (BS1, BS4, and BS5) ranged from 1.2 to 2.4 and 1.3 to 2.7, respectively, suggesting a moderately polluted category. On the other hand, the higher I_{geo} values were observed for sampling sites in Nam Son (NS2 and NS5) and Bac Son (BS2 and BS3) indicating a greater influence from the landfill in the soil nearby area. This finding highlights the potential impact of the landfill on the soil in its surrounding area.

2.4. Conclusions

Based on the analysis results of soil samples in paddy fields around Nam Son landfill in Hanoi, Vietnam, this study provides an initial report on the mercury accumulation in agricultural land around Nam Son landfill. The paddy fields selected in this study are contaminated with Hg through landfill operations. The geo-accumulation of Hg in paddy fields near landfills is significant. This can lead to a potential risk of Hg contamination in agricultural products grown in this area. Therefore, strict control measures are needed in classifying and treating waste before it is buried.

The spatial and seasonal distribution of Hg in soil is influenced by the physical factors such as monsoons, precipitation regime. Heavy rainfall in the rainy season increases the evaporation of Hg, leading to the amount of Hg in soil in the rainy season tending to be lower than in the dry season. SOM has a positive correlation with the amount of Hg in both soil layers ($p < 0.05$). While this study sheds light on Hg accumulation in agricultural soil around the Nam Son landfill, and the influence of SOM, monsoons and precipitation regime on the spatial distribution of Hg in the soil, it is important to note that these are just some of Hg transport and accumulation in the soil. Thus, it is important to keep in mind that more detailed research is needed to further elicidate the factors affecting the distribution and accumulation of Hg in soil in this area, to find out the detailed impacting mechanism of soil properties on Hg accumulation then reduce the negative impact on soil Hg .

Chapter 3: The health risk assessment of mercury in rice from paddy fields around Nam Son landfill, Hanoi, Vietnam

Citation:

Nguyen Thi Quynh, Huiho Jeong, Ahmed Elwaleed, Yasuhiro Ishibashi and Koji Arizono (2024). The health risk assessment of mercury in rice from paddy fields around Nam Son landfill, Hanoi, Vietnam. Fundamental Toxicological Sciences. **2024**, Vol. 11, No. 3 https://doi.org/10.2131/fts.11.99

3.1. Introduction

Mercury (Hg) is one of the ten most toxic elements that affect on human health, in the natural, Hg exist in the three form: elemental mercury or quicksilver (metallic mercury and vapor mercury, Hg^0), inorganic mercury (Hg^+ and Hg^{2+}), and organic mercury (methylmercury and ethylmercury), from natural sources (volcanic emission, cinnabar) and anthropogenic sources (coal-fired electric utilities, waste combustion, and hazardous-waste incinerators (Cariccio et al.,2019). Hg compounds can cause kidney failure, nervous system disorders, fetal toxicity, and death (Cariccio et al.,2019; Fernandes et al., 2012). One of the most serious Hg poisoning cases in history was the Minamata disaster in Japan, which caused the deaths of 1043 people, the reason is consumption contaminated fish and shellfish by the discharge activities of factory manufacturing the chemical acetaldehyde (Harada, 1995). Hg is unique heavy metal due to its toxicity, long-distance transport, persistence and bio-accumulation (Wang et al., 2016).

Rice consumption has recently been considered by researchers as one of the main routes of mercury exposure to the human body through the food chain besides fish (Horvat et al., 2003; Du et al., 2021). Paddy fields are a very special environment, not only the amount of Hg accumulated from the air, but rice soil also accumulates mercury from cultivation such as irrigating farmland with Hg-contaminated water, extensive use of fertilizers, and pesticides containing Hg (Huang et al., 2022). In particular, paddy fields located near anthropogenic sources such as artisanal and small-scale gold mining (ASGM) (Qiu et al., 2008), industrial areas, and landfills (Tang et al., 2015) are increased risk potential for Hg contamination (Tang et al., 2020). Numerous studies have shown that rice, fish, and fruits harvested from area located near sources of mercury pollution is contaminated with significant amounts of Hg (Peng et al., 2015; Wu et al., 2013).

Rice (Oryza sativa) is a staple food crop, and Vietnam is one of five major rice exporters (India, Pakistan, Thailand, the US and Vietnam) (WEF, 2022). The Red River Delta (RRD) located in the North of Vietnam is the second largest granary in the country, behind Mekong Delta located in the South. The average annual rice cultivated area of RRD is roughly 1.07 million hectares (Vietnam General Statistics Office - GSO), accounting for about 14% of Vietnam's total rice growing area (USDA, 2020) , also is the second largest granary in the country. With the advantage of favorable terrain, RRD is a large plain, supplied with annual alluvium from the Red River, creating fertile land and creating favorable conditions for cultivating crops. RRD has two main crops a year: the summer rice crop and the Summer-Autumn crop.

In Vietnam, rice products are always fully utilized. Besides rice, other products including bran, rice husk, and straw are also used. Specifically, rice bran is the outer brown layer, including the rice germ that is removed during milling of brown rice to produce milled rice (Rosniyana et al., 2009), which is used as food for livestock (pig, cow, chicken, duck, etc.). Rice husk are used as fertilizer, barn bedding, fuel, and mushroom growing material. Straw is used as food for cattle, fertilizer, and fuel. Therefore, Hg pollution in rice not only affects the quality of rice but also affects the quality of livestock and the environment, hence Vietnam is the third country had the highest Hg production density (behind Bangladesh and India) (Liu et al., 2019).

In this study, we collected rice samples from paddy fields surrounding the Nam Son landfill area to evaluate the level of Hg contamination in rice around landfill area. The influence of manual drying method on Hg level in rice was discussed. Besides, for the first time, potential health risk assessment based on local resident's consumption of rice harvested from the study area.

3.2. Materials and methods

3.2.1. Sampling site

The study site is in paddy field around Nam Son landfill site in Soc Son district of Hanoi, Vietnam, located in Red River Delta (RRD), where is the primary region for rice cropping in northern Vietnam (Nguyen et al., 2015).

Nam Son waste treatment complex has a total area of 83.5 hectares, including a wastewater treatment plant, a waste power plant and closed and operating landfills (**Figure 3.1**). The process of transporting, burying and treating waste can release toxic substances including organic compounds (Andrew et al., 2011) and heavy metals (Hoai et al., 2021; Giang et al., 2018) into the environment around the landfill. This study focuses on assessing the level of mercury contamination in rice from paddy fields surrounding Nam Son landfill. Due to terrain characteristics and incomplete planning, some rice fields are only 200 m from Nam Son landfill. In previous research we have demonstrated that rice paddy soil surrounding the landfill area is likely to be contaminated with Hg from the landfill (Thi Quynh et al., 2024), therefore a study to evaluate the absorption and transport of Hg from the soil into rice plants in this area is really necessary.

3.2.2. Sample collection

Sampling campaign was conducted in the paddy fields around Nam Son landfill on September 15th 2021, during the Summer-Autumn harvesting season. A total of 15 rice samples (**R01 – R15**) were collected in Nam Son and Bac Son commune, using a sickle. After collection, all rice samples were washed with tap water 3 times and rinsed with milli-Q water. They were dried in the oven at 40 °C for two weeks. Then, husks were separated from grains by a huller. Brown rice and husk samples were ground using a porcelain mortar and pestle and sifted through a 200 μm mesh size sieve to obtain finer particles. The dried samples were labeled and stored in a polyethylene ziplocked bags and kept at 4 °C.

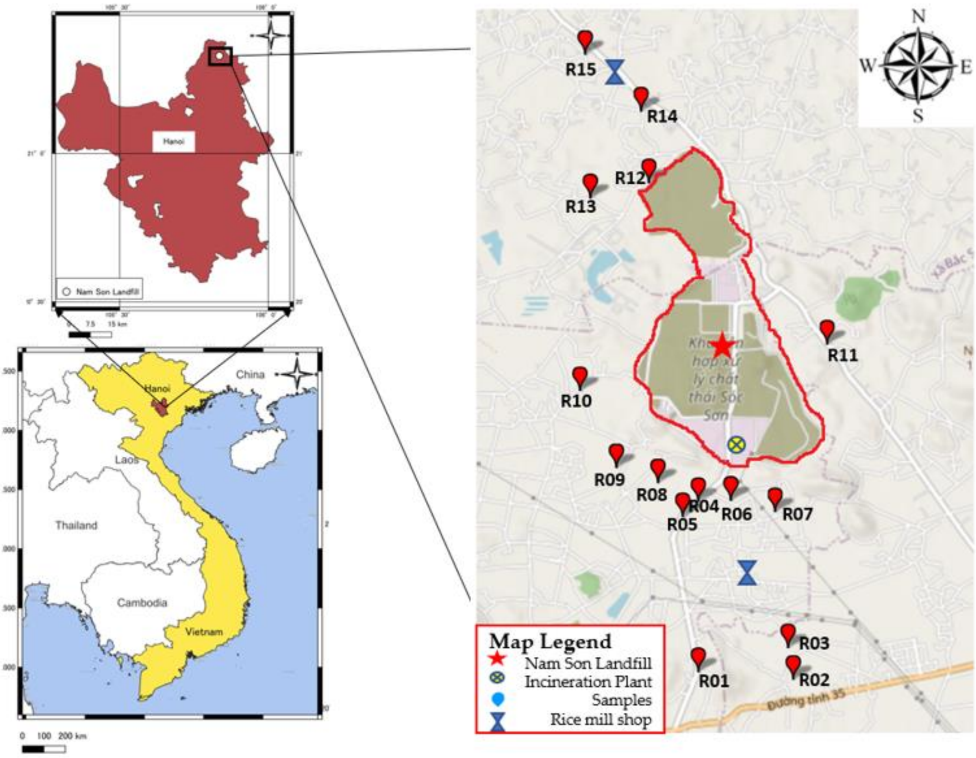


Figure 3.1. Map of sampling site, Nam Son, Soc Son, Hanoi

In addition, due to the farming habits rice is often dried on the ground of garden, road or highway under sunlight, leading to the rice being contaminated with Hg.

Therefore, ten polished white rice and its rice bran (n = 10, and n = 10) were collected at mill shops located in Bac Son commune and Nam Son commune. At the mill shops, rice was milled removing the husk, bran layers and germ. Polished white rice, and rice bran were then ground using a porcelain mortar and pestle and sifted through a 200 μm mesh size sieve to obtain finer particles. The dried samples were labeled and stored in a polyethylene ziplocked bags and kept at 4 °C in the dark.

3.2.3. Sample analysis

a) Hg analysis

The Hg concentration in all samples were determined using the direct thermal decomposition mercury analyzer (MA-3000, Nippon Instruments Corporation, Tokyo, Japan). Approximately 50 mg of each sample was weighed into sample boats in triplicates and placed in MA-3000. Calibration curves were generated using standard solutions of Hg^{2+} at concentrations of 10 μg/kg, 100 μg/kg and 1000 μg/kg for both low and high calibration curves.

b) Ecological Risk Assessment

Potential ecological risk index (PER) was employed using the Hakanson, 1980 model. This index considers the sensitivity of biological communities, toxicity, measured concentration and background concentrations. Hg contamination coefficient (C) was calculated using Equation 1. Then potential ecological risk index (PER) of Hg was calculated using Equation 2. Input parameters for these equations are detailed in **Table 3.1**.

$$\mathbf{C = C_{Hg}/B_{Hg}} \text{ (Equation 1)}$$

C < 1: low contamination factor (indicating low sediment contamination of the substance in question); **1 < C < 3**: moderate contamination factor; **3 < C < 6**: considerable contamination factor; **C > 6**: very high contamination factor.

$$\mathbf{PER = C \times T} \text{ (Equation 2)}$$

PER < 40: low risk, 40 ≤ PER < 80: moderate risk, 80 ≤ PER < 160: considerable risk, 160 ≤ PER < 320: High risk, PER ≥ 320: very high risk.

Table 3.1. Input parameters for evaluating Hg concentration coefficient (C), and Potential ecological risk index (PER)

Parameter	Meaning	Value (unit)	Reference
$\mathbf{C_{Hg}}$	Hg concentration in rice	(µg /kg)	This study*
$\mathbf{B_{Hg}}$	the local Hg concentration background for soil	7.47 (µg /kg)	Thi Quynh et al., 2024
T	The toxic factor of Hg	40	Hakanson et al., 1980

Table 3.2. Input parameters for evaluating Estimated Weekly Intake (EWI_{hm}) and Hazard Quotient (HQ)

Parameter	Meaning	Value (unit)	Reference
EF	The exposure frequency	365 (days/year)	USEPA, 1989

ED	The exposure duration	70 (years)	USEPA, 1989
IR_{hm}	The rice grain ingestion rate	0.589 (kg/day)	Chu et al., 2021
C_{Hg}	The concentration of Hg in rice grain	(μg /kg)	This study*
φ	The bio-accessibility of Hg	45 (%)	(Lin et al., 2019)
BW_{hm}	The average body weight	58 for male and 45 for female (kg)	(Chu et al., 2021)
AT	The average exposure time for non-carcinogens	For non-carcinogens, AT = ED × EF	USEPA, 1989
RfD	The oral reference dose of Hg via the oral exposure route	0.0003 (mg/kg/d)	Jin et al., 2023

c) Tolerable intake of Hg and risk characterization

For human

Health risks associated with Hg calculated using the model in the FAO/WHO Joint Expert Committee on Food Additives (JECFA) withdrew the former Provisional Tolerable Weekly Intake (PTWI), it indicates the noncarcinogenic risk of oral exposure. The JECFA established a PTWI for inorganic Hg is 4 μg /kg b.w. The Estimated Weekly Intake (EWI_{hm}) of Hg from consumption of rice can be calculated by Hg concentration in rice with the consumption levels per week dividing by the average body weight of the population by sex, using the Equation 3 (Ahmad et al., 2022).

Health risks associated with Hg calculated using the Hazard quotient (**HQ**) was used to estimate the probability of health effects due to the exposure through consumption of rice. The following Equation 4 was used to calculate HQ.

Input parameters for these equations are detailed in **Table 3.2**.

$$\mathbf{EWI_{hm} = (IR_{hm} \times 7 \times C_{Hg} \times \varphi)/ BW_{hm}} \quad \text{(Equation 3)}$$

$$\mathbf{HQ = (EF \times ED \times IR_{hm} \times C_{Hg} \times \varphi) / (BW_{hm} \times RfD \times AT)} \quad \text{(Equation 4)}$$

HQ < 1: no negative noncarcinogenic health effects for the exposed human population, **1 ≤ HQ**: the pollutant is likely to have some noncarcinogenic deleterious effects on human health.

For Chicken

The Feed Daily Intake (FDI) of Hg from consumption of rice bran by chickens can be calculated based on Hg concentration in rice bran. The hypothetical chickens considered in this study were commercial broiler chickens (Hybro strain), using the Equation 5 (Ahmad et al., 2022).

$$\mathbf{FDI_{ck} = (IR_{ck} \times C_{HgRB})/ BW_{ck}} \quad \text{(Equation 5)}$$

Where:

$\mathbf{IR_{ck}}$**:** the rice bran ingestion rate (0.15 kg/kg/day (Zhang et al., 2020))

$\mathbf{C_{HgBR}}$**:** the concentration of Hg in rice bran (μg /kg)

BW_{ck}: The average chicken weight (0.22 kg (Atuahene et al., 2000))

3.2.4. Quality assurance (QA) and quality control (QC)

In the laboratory analysis, strict measures were taken to ensure a contamination-free environment. An ultra-clean bench was used, and all water used had a high purity level of 18.2 MΩ·cm @ 25°C (Millipore, USA). Reagents of guaranteed purity (GR) were utilized to avoid any contamination or ultra-low blanks.

During the analysis of ultrapure water was employed as a blank to establish baseline measurements. To ensure the accuracy and reliability of the Hg analyses, a comprehensive quality assurance and quality control program was implemented. Method blanks, certified reference materials (CRM), specifically ERM-CC580 (Institute of Reference Materials Measurements, Belgium) for Hg, and duplicate samples were used. The obtained results from this method demonstrated excellent agreement with the reference values, with a mean value of 132 ± 3 mg/kg. The recovery rates for the certified reference materials ranged from 96.9% to 101.7% for the Hg analysis, and the relative standard deviations were consistently < 5 % for Hg.

3.2.5. Statistical analysis

The statistical analysis was conducted using IBM SPSS Statistics SPSS 26.0 software from IBM Corporations, New York, USA. The Shapiro-Wilk was used to assess whether data might be well-described by a Normal distribution. The dietary exposure levels for Hg by sex and residential area categories were compared by one-way analysis of variance (ANOVA). Graphs were crafted utilizing OriginPro and Microsoft Excel.

3.3. Results and discussion

3.3.1. Hg concentration in rice

Hg concentration in brown rice was shown in **Figure 3.2**. The mean concentrations of Hg in brown rice measured at Nam Son and Bac Son were 11.3 ± 1.08 µg/kg and 8.81 ± 1.22 µg/kg, respectively.

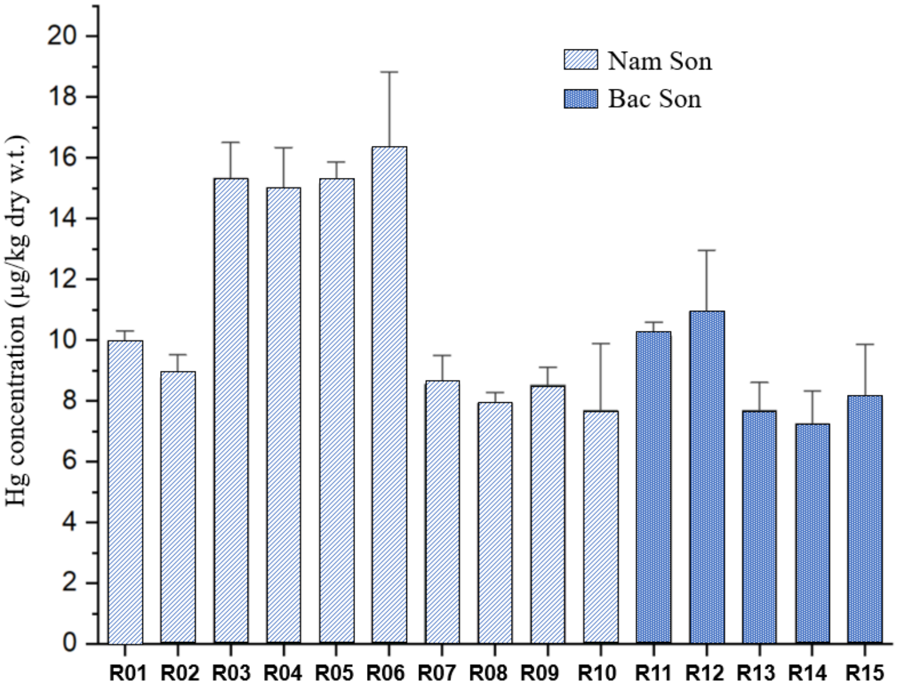


Figure 3.2. Hg concentration in brown rice samples.

Specifically, sampling points with higher Hg concentrations include R03, R04, R05, R06 with Hg concentration ranging from 15.0 ± 1.39 µg/kg to 16.3 ± 2.57 µg/kg. It can be seen that these are all locations in Nam Son located near the main gate and close to the landfill. A similar trend was also observed in Bac Son, R11 and R12 (10.2 ± 0.47 µg/kg and 10.9 ± 1.81 µg/kg) located near roads and the landfill had higher Hg concentrations than other sites. This may be explained by the fact that during the time these rice samples were collected, the Thien Y waste power plant located near the south gate of the landfill was under construction (September 2021). Therefore, besides garbage trucks, a large number of trucks transporting construction materials pass through Nam Son Street to the south gate of the landfill. This contributes to increased mercury concentrations in the environment in the southern region, leading to higher Hg concentrations in rice grains.

Similar mean ± SD Hg concentration have been reported from Hg-contaminated site in Pakistan in the study of Aslam M W *et at*., 2020 (12.20 ± 16.97 ng/g). Chu *et at*., 2021 reported Hg concentration in rice in not Hg-contaminated and mining activity area was 7 (nd – 11) µg/kg. Compared with the study of Du *et al*., 2018 conducted with rice samples collected in areas not contaminated with Hg, with an average value of Hg concentration in rice samples of 4.6 ± 3.0 µg/kg in Hubei and 3.9 ± 1.6 µg/kg in Anhui, China (Du et al., 2018), brown rice samples from the area around Nam Son landfill had higher Hg concentrations. This indicated that rice grown in this area is contaminated with a certain amount of Hg from Nam Son landfill.

However, compared with the reported data of Hg concentration in rice of ASGM area in Lebaksitu, Indonesia was 32.2 (9.1 – 115) µg/kg (Novirsa et al., 2020), Hg mining area of 10.3 – 1120 µg/kg of dry w.t in Guizhou, China (Qiu et al., 2008), and 643 µg/kg at the Xunyang Hg mine located in Shaanxi Province, China (Ao et al., 2020), the data obtained from this study was much lower. Because the brown rice collected in this study area is contaminated with Hg from Nam Son landfill, although the degree of impact is there, to compare with areas Hg-contaminated by Hg mining, and ASGM, its concentration is extremely small.

Hg concentration in ten polished white rice and bran rice from mill shops in Nam Son and Bac Son commune are shown in **Figure 3.3**. Both the Hg concentration in polished white rice and rice bran in Nam Son and Bac Son were far below the recommended Vietnamese guideline values of 50 μg/kg for coffee, tea and its products (QCVN 8-2:2011/BYT, 2011). All the samples, Hg concentration in rice brans are higher than its polished white rice, Hg concentration in rice bran are almost equal twice Hg concentration in polished white rice.

Rice bran is a by-product of rice industry containing about 87% dry matter, 11–15% crude protein, 15–20% lipids and 6.5–10% ash (de Campos et al., 2007). Rice bran are feed livestock, hence higher concentrations of Hg in rice bran will increase the potential risk of Hg contamination. Hg pass through the food chain causing a potential risk of Hg exposure to humans. An investigation into the amount of rice bran used for livestock production and food consumed by people every day is urgently needed in the next study.

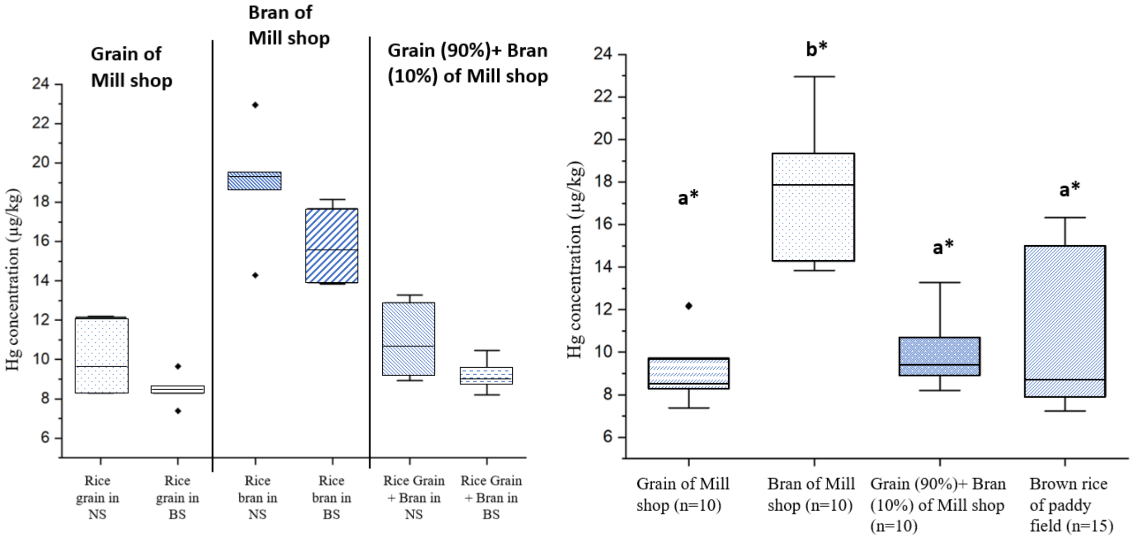


Figure 3.3. Hg concentration in ten polished white rice (grain rice) and bran rice from mill shops in Nam Son commune (NS) and Bac Son commune (BS)

Figure 3.4. Comparison between Hg concentration in polished white rice (grain rice) and bran rice from mill shop and brown rice from paddy field.

* The same letters represent no significant difference ($p > 0.05$) and the different letters represent a significant difference ($p < 0.05$) by the one-way ANOVA test

On the other hand, according to Nurul Husna Shafie and Norhaizan Mohd Esa, 2017 researched on the structure of rice grain, rice husk accounts for 20% and brown rice accounts for 80% (of which is rice bran 8%, white rice is 70%, and rice germ is 2%). Based on the structure of rice, we estimated the amount of Hg present in brown rice from the mill shop equivalent to 90% of the Hg concentration in polished white rice (grain rice) plus 10% of the Hg concentration in bran rice (**Figure 3.4**). The result indicating no signification difference between brown rice from mill shops and paddy fields. However, Hg concentration in all bran samples were signification higher than white rice and brown rice from mill shops and paddy fields. Probably suggesting that rice grains absorb Hg from atmosphere such as dry and wet deposition, vehicles, fertilizers, and pesticides containing Hg (Huang et al., 2022). Previous studies have confirmed that Hg uptake from rice root hardly transported into rice aerial parts, and Hg absorbed rice grain is mainly in the gaseous elemental Hg (Hg^0_g) entering through stoma (Tang et al., 2020). Recently, research by Phan Dinh et al., 2022 also detected a relatively high amount of Hg in street dust in Hanoi city. Therefore, the amount of Hg accumulated from the air environment in the bran covering rice grains during maturation has led to the amount of Hg in rice bran being higher than rice grain.

Comparing the Hg concentration between brown rice from paddy fields in Nam Son and Bac Son commune, we observed that Hg concentration in brown rice of Nam Son was higher than its of Bac Son, however, the previous study showed that Hg concentration in soil of Nam Son was lower than its of Bac Son (Thi Quynh et al., 2024). This indicated that Hg concentration in soil has no significant effect on Hg concentration in rice, while Hg soil contamination is related to the cannel, drain water of the wastewater plant (the north gate of the landfill), but air contamination is one of essential factors of the rice samples. Ao *et al*., 2020 also demonstrated that significant Hg accumulation in rice grains is a result of atmospheric mercury deposition. Some previous studies have shown that the Hg content accumulated in street dust is higher in soil (Nguyen *et al*., 2022; Sahakyan *et al*., 2018).

3.3.2. Ecological Risk Assessment

The results for the contamination coefficient (C), and potential ecological risk (PER) index are shown in **Table 3.3**. Base on the assessment, the brown rice from both Nam Son and Bac Son had $1 < C < 3$, indicating moderate contamination factor. The brown rice from both Nam Son and Bac Son had $40 \leq PER < 80$, indicating moderate risk. Hence, all the rice from paddy field around Nam Son landfill may pose potential ecological risks to human, livestock, and the entire paddy field ecosystem. However, continuous release of Hg through landfill activities into the surrounding area may result in higher contamination of the paddy fields and their produce in future.

Table 3.3. The C and PER values of brown rice in Nam Son and Bac Son commune.

Location		Concentration (µg/kg) (min – max)	C	PER
Rice paddy field	Nam Son (South of the landfill)	11.31 (7.68 - 16.32)	1.51	60.6
	Bac Son (North of the landfill)	8.81 (7.23 – 10.94)	1.18	47.2

3.3.3. Health risk assessment

To evaluate the dietary exposure risk from rice grains, we analyzed the estimated weekly intake (EWI) of Hg through polished white rice from mill shop and brown rice for human and rice bran for chickens. The bio-accessibility of Hg in this study used a value of 45 % (Lin et al., 2019), applied to cooked rice. Considering the worst-case scenario, with the highest Hg bio-accessibility values. Compared to the bio-accessibility for fish, this ratio was lower, Bradley *et al.*, 2017 reported up to in raw tuna 75%, and 75 – 92 % in raw shrimp (Siedlikowski et al., 2016), however the bio-accessibility is reduced if the food is cooked (Abdullah, 2020).

Table 3.4. $\mathrm{EWI_{hm}}$ and HQ level of polished white rice and brown rice, and $\mathrm{FDI_{ck}}$ level of rice bran from Nam Son and Bac Son commune

Location			**Concentration (µg/kg) (min – max)**	**Male**		**Female**		**Chicken**
				$\mathbf{EWI_{hm}}$ (µg/kg b.w)	**HQ**	$\mathbf{EWI_{hm}}$ (µg/kg b.w)	**HQ**	$\mathbf{FDI_{ck}}$ (µg/kg b.w)
Rice mill shop	Nam Son (South of the landfill)	Polished white rice	10.4 (8.47 – 12.2)	0.333	0.158	0.429	0.204	N/A
		Bran rice	19.5 (15.9 – 22.9)	N/A	N/A	N/A	N/A	2.91
	Bac Son (North of the landfill)	Polished white rice	8.47 (7.39 – 9.65)	0.271	0.129	0.349	0.166	N/A
		Bran rice	15.8 (13.8 – 18.2)	N/A	N/A	N/A	N/A	2.37
Rice paddy field	Nam Son (South of the	Brown rice	11.3 (7.68 - 16.3)	0.364	0.172	0.469	0.222	N/A

landfill)							
Bac Son (North of the landfill)	Brown rice	8.81 (7.23 – 10.94)	0.280	0.134	0.364	0.173	N/A

N/A: no applied

The average EWI_{hm} value of Hg through consumption of polished white rice from mill shop is 0.333 μg/kg b.w and 0.271 μg/kg b.w for male, and 0.429 μg/kg b.w and 0.349 μg/kg b.w for female in Nam Son and Bac Son commune, respectively (**Table 3.4**). This value with consumption of brown rice from paddy fields is 0.364 μg/kg b.w and 0.280 μg/kg b.w for male, and 0.469 μg/kg b.w and 0.364 μg/kg b.w for female in Nam Son and Bac Son commune, respectively. Generally, EWI_{hm} of brown rice was higher the polished white rice. All values were lower than the PTWI of JECFA established for inorganic Hg is 4 μg/kg b.w. Along with that HQ values of male and female in Nam Son and Bac Son all were lower than one, indicating that consuming rice from Nam Son and Bac Son might not cause potential human health risk of Hg exposure.

The average FDI_{ck} value of Hg through consumption of rice bran from mill shop is 20.4 μg/kg b.w and 16.6 μg/kg b.w for chicken in Nam Son and Bac Son commune, respectively (**Table 3.4**). FDI_{ck} values in chickens are high, suggesting that a large amount of Hg is absorbed by chickens. That amount of Hg can accumulate in chicken parts and affect human health through the food chain. In this study, the Hg concentration in chicken parts such as meat, skin, stomach, liver and bones were not evaluated. Therefore, a future study evaluating the Hg content in chicken parts such as muscle, skin, bond and egg is necessary.

3.4. Conclusions

Based on the analysis results of rice samples from paddy fields around Nam Son landfill, Hanoi, Vietnam, this study showed the condition of Hg in rice planted in this area. The Hg concentrations in brown rice samples from paddy fields of this study ranges 7.18 ± 0.73 to 16.32 ± 2.57 μg/kg dry w.t. Among them, brown rice samples near landfill or highway tend to have higher Hg concentrations than sites farther away. This result indicates that activities related to traffic and construction sites may play an important role in the dispersion of Hg in the study area.

The brown rice from both Nam Son and Bac Son had $40 \leq PER < 80$, indicating rice from paddy field around Nam Son landfill pose potential ecological risks to human, livestock, and the entire paddy field ecosystem.

HQ was calculated to assess the potential health risk of Hg in this study. HQ values of male and female all were less than one, it demonstrated a relatively low risk of Hg ingestion cause by rice consumption planted in paddy fields around Nam Son landfill. However, the FDI of chickens are high, suggesting that a large amount of mercury is absorbed by chickens through the consumption of rice bran, thereby causing a potential risk to human health through the food chain.

Chapter 4: Hair mercury levels of resident in Nam Son landfill area, Soc Son, Hanoi

4.1. Introduction

Vietnam is experiencing a period of strong urbanization. Migration from rural to urban areas, along with the expansion of administrative boundaries of urban area, has rapidly increased the proportion of the population living in urban areas. This has resulted in environmental pollution problems and domestic waste reaching overload level. Specifically, in Hanoi city, over 5000 tons of domestic waste are generated daily (Giang et al., 2018). This waste is gathered without any classification process and then transported to Nam Son landfill. Most of the waste is buried, part of which is used as fuel for the Thien Y waste power plant. Landfilling and incineration can lead to Hg leaching into soil and water, as well as releasing them into the air (He et al., 2018; Zhu et al., 2013).

Mercury is a common metal that can be found in many products, such as thermometer, batteries, fluorescent lights, electric switches, and electronic equipment (Tan et al., 2015). Hg is a liquid under normal conditions, however, it can exist in its metallic form, as vapor, or transform into a more toxic form known as MeHg (Wu et al., 2024). Hg can damage neurological, nephrological, immunological, cardiac, motor, reproductive, and even genetic systems（Gibb & O’Leary, 2014）. Human exposure to Hg occurs through ingestion (food chain), skin contact, and inhalation (Kim et al., 2016). Additionally, residents in particularly polluted areas such as Nam Son landfill may be indirectly exposed through physical contact with contaminated soil, dust, air, water, and food.

Rice is a staple food in the human diet, making it crucial to give more attention to the potential risk of Hg exposure through the rice food chain. Rice cultivation plays a significant role in the global Hg cycle. Burning rice residues can increase atmospheric Hg emissions, while residues that degrade in paddy soils can enhance MeHg accumulation in rice grains (Ao et al., 2020; Liu et al., 2019). This raises a concern that rice consumption may serve as another significant pathway for human Hg exposure (Zhao et al., 2018). Residents in areas with higher rice consumption may therefore face an elevated risk of Hg exposure.

Hair Hg concentrations are widely used as a biomarker Hg exposure in humans. Human hair is an ideal tool for health investigations because hair sampling is both convenient and non-invasive. This method has been explored for medical applications, disease states, and pollutant exposure (Thompson et al., 2013), the content of THg or MeHg in hair correlates with Hg level in the blood (Srogi, 2007). The concentration of Hg in hair is significantly higher than in blood (Liberda et al., 2014), allowing easier detection of Hg.

Recent studies have shown that rice consumption from in Hg-contaminated paddy soil is a major pathway for Hg exposure in local populations. However, the level of Hg exposure to residents near the Nam Son landfill, and the dietary contribution to this exposure, remains unclear. Therefore, in this study, we conducted measurements of the contaminants in rice plants and the hair of residents in the Nam Son landfill area. The aims of this study were as follows: 1) to evaluate Hg accumulation in human hair samples; and 2) to estimate the contribution of rice consumption to Hg exposure in local residents around the Nam Son landfill, to provide a reliable theoretical and scientific basis for the regulation and safe utilization of Hg-contaminated rice.

4.2. Materials and methods

4.2.1. Study area

Our study was conducted in Nam Son landfill area, located in the Red River Delta in northern Vietnam (**Figure 1**). The Nam Son landfill, part of the Nam Son Waste Treatment Complex, initially covered 83.5 hectares, with 53.49 hectares designated for landfill purpose. In 1999, during its first phase, it was designed to process around 2000 tons of waste daily (Giang et al., 2018). Up to now, the landfill has been operating for 25 years, serving as the site where waste from Hanoi city is buried and treated. Two communes were selected in our study, Bac Son commune (north of the Nam Son landfill) and Nam Son commune (south of the Nam Son landfill). Rice paddy fields in these two communes are cultivated near the landfill, with some as close as 200 meters from the site, leading to the rice in this area being affected by Hg (Quynh et al., 2024).

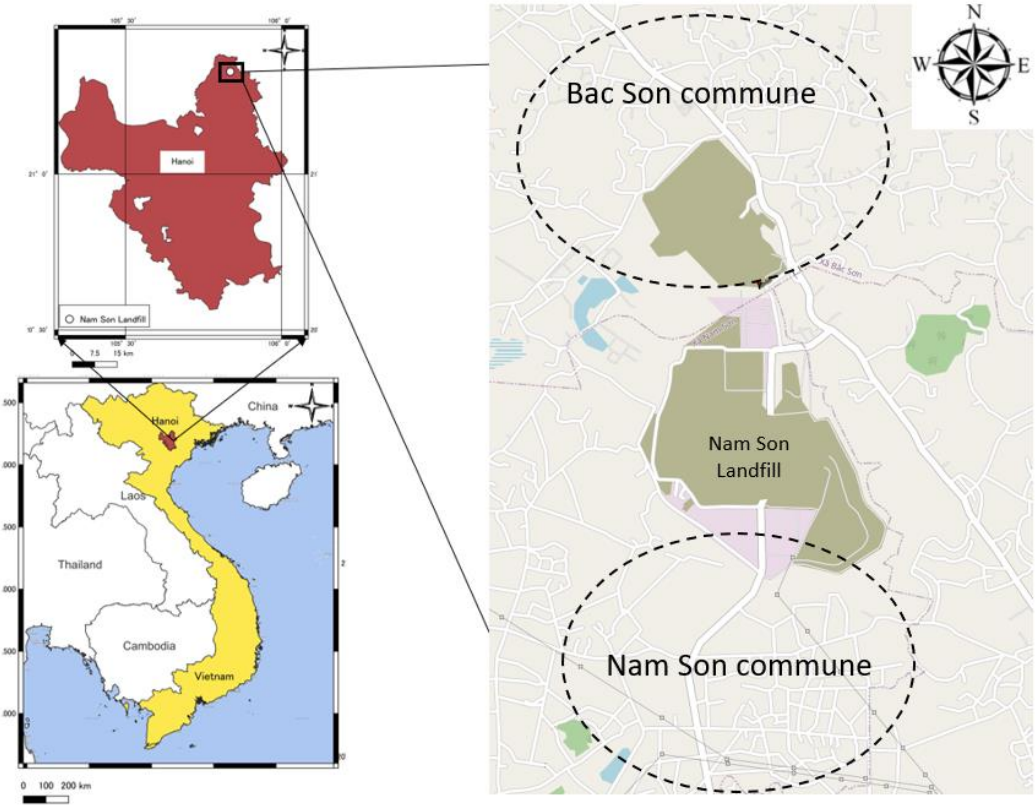


Figure 4.1. Map of study area

4.2.2. Questionnaire survey

The Prefectural University of Kumamoto ethic committee has approved the research condition and method of this study. Epidemiological data were collected using a WHO-recommended health risk assessment questionnaire for Nam Son landfill. In March 2024, a total of 16 participants' personal identification were collected through a face-to-face interview in the survey, all participants were selected randomly. The survey groups were composed of all males who lived in Bac Son (BS, n = 9) and Nam Son (NS, n = 7) commune around the Nam Son landfill. We investigated the occupation, age, height, weight, smoking and alcohol drinking habits for individuals. Furthermore, to identify the effect of rice consumption on human Hg expose, this study considered the daily intake of rice via the questionnaires. These participants appeared to be healthy, with no confirmed Hg exposure, major congenital anomalies, or other disease. Prior to the interview, participants were informed about the purpose of this survey and provided with an informed contest document. Participants who rejected the informed consent were excluded from the study. The personal information is confidential and will not be disclosed to public. It will be used solely for statistical analysis purposes.

4.2.3. Sample collection and preparation

Hair samples were collected following the United States EPA-7473 method. Scalp hair samples were cut with clean stainless steel scissors, about 0.5 – 1.0 cm in length, placed into clean and sealed polyethylene bags, and transported to the laboratory. Hairs were disposed into short segments, washed with nonionic detergent, sonicated for 10 min and triple-rinsed with distilled water and acetone, respectively. The samples were then dried in an oven at 40 °C overnight for further analysis (Xie et al., 2021).

4.2.4. Analytical methods

For Hg, dried samples about 30 mg were weighed into sample boats in triplicates and then sent into the direct thermal decomposition mercury analyzer (MA-3000, Nippon Instruments Corporation, Tokyo, Japan) following US EPA Method 7473. Calibration curves were generated using standard solutions of Hg^{2+} at concentrations of 10 μg/kg, 100 μg/kg and 1000 μg/kg for both low and high calibration curves.

4.2.5. Quality assurance/quality control (QA/QC) and data analysis

For each batch of Hg analysis, quality control was assured by triplicating every tenth sample along with additive B blanks method to establish baseline measurements. To ensure the accuracy and reliability of the Hg analyses, a comprehensive quality assurance and quality control program was implemented. Certified reference materials (CRM), specifically ERM-CC580 (Institute of Reference Materials Measurements, Belgium) for Hg, and triplicate samples were used. The recovery rates for the certified reference materials ranged from 96.9% to 101.7% for the Hg analysis, and the relative standard deviations were consistently < 5 % for Hg.

The statistical analyses were performed using SPSS 26.0 (IBM, NY, USA) and Origin 2023 (OriginLab, Corporation, MA, USA). Differences between groups were tested using t-test analysis. The $p < 0.05$ was considered statistically significant.

4.3. Result and discussion

4.3.1. Hair Hg concentration

The hair Hg concentration in Bac Son and Nam Son communes ranged from 0.47 mg/kg to 2.08 mg/kg ($n = 9$) and 0.41 mg/kg to 1.28 mg/kg ($n = 7$), respectively, with the mean of Hg concentration in hair was 0.88 ± 0.05 mg/kg ($n = 16$) (**Figure 2**). Among them, about 31 % participants (5 samples) exceeded the safety standard of 1 mg/kg for hair Hg recommended by the US EPA (US EPA, 1997). There was no statistically significant difference in Hg concentrations in hair from Bac Son and Nam Son commune. The highest Hg concentration was observed in sample H9 (landfill worker), the lowest Hg concentration was found in H14 (non-landfill worker).

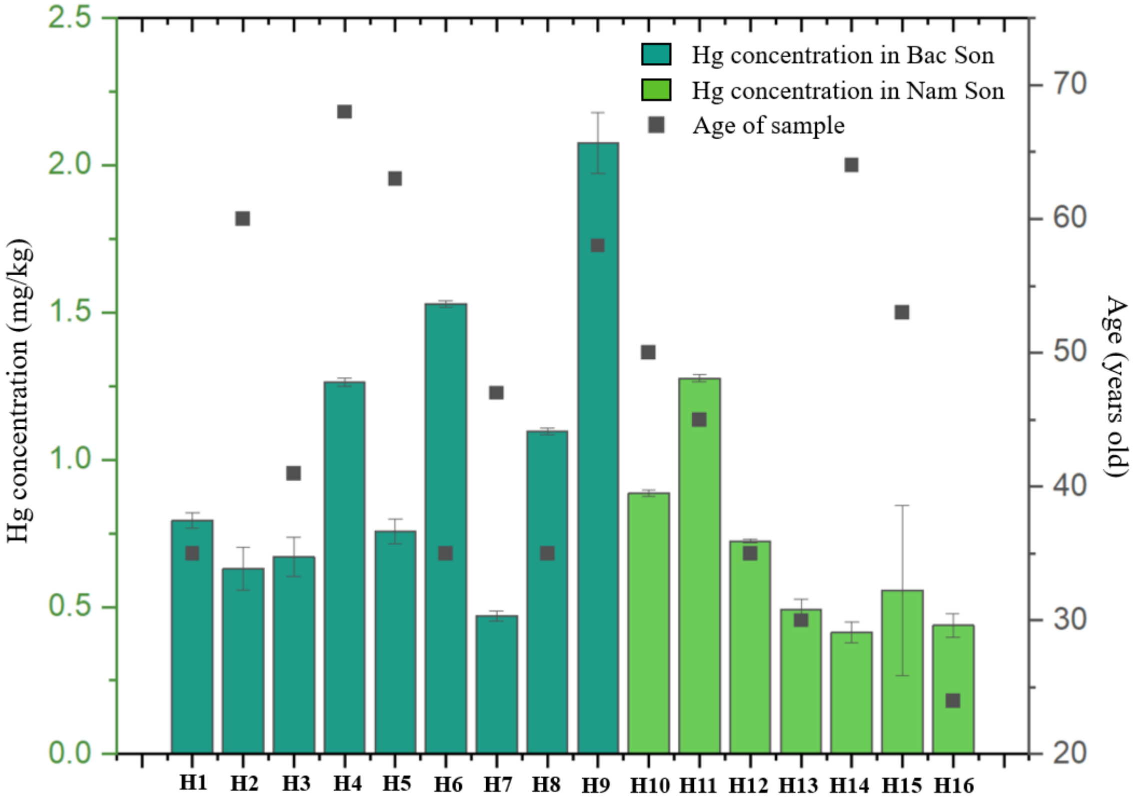


Figure 4.2. Hg concentration in hair samples around Nam Son landfill

Table 1 shows the comparison of Hg concentration in hair from the Nam Son landfill area and other studies. The hair Hg concentration in this study was higher than that in the hydroelectric area of China, where the hair Hg concentration was 0.42 ± 0.43 mg/kg and Hg concentration in Hg mining area in Colombia (0.86 mg/kg). However, the hair Hg concentration in this study was lower than the mean concentration of 3.2 (0.85 – 9.15) mg/kg in hair from the ASGM area of Indonesia and the Hg-contaminated site in Brazil.

Table 4.1. Comparison of Hg concentration in hair in Nam Son landfill area and other studies.

Location	**Hg concentration (mg/kg)**	**Reference**
Nam Son landfill (Hanoi, Vietnam)	0.88 ± 0.05 (*n* = 16)	This study
Hydroelectric area (China)	0.42 ± 0.43 (*n* = 540)	Xie et al., 2021
Hg mining area (Colombia)	0.86 (*n* = 96)	Suárez-Criado et al., 2023
ASGM (Lebaksitu, Indonesia)	3.2 (0.85 – 9.15) (*n* = 41)	Novirsa et al., 2020
Hg-contaminated site (Brazil)	9.8 – 17.5 (*n* = 36)	Dolbec et al., 2001

Although the Hg concentration in the soil around the Nam Son landfill area was not high (Thi Quynh et al., 2024), the Hg concentration in the hair of residents in this area is quite elevated. The observed discrepancy may be due to Hg concentration in hair being influenced by Hg in the air. Information collected from residents indicates that garbage burning at this landfill usually occurs in the evening. Incineration and the operating waste power plant are potential sources of significant Hg emissions into the surrounding environment, directly impacting the health of residents in the area around the landfill.

In our study, we considered total Hg in hair, which serves as a reliable indicator of methylmercury (MeHg) exposure. MeHg is reported to account for 85 – 98 % of THg in human hair (Wang et al., 2021a). Tang et al. (2015) showed that approximately 81% of Hg in hair exists in the form of MeHg (Tang et al., 2015). Assuming that the amount of MeHg in the hair of residents in this area accounts for 81% of THg, the hair MeHg concentration in Bac Son and Nam Son communes ranges from 0.38 to 1.68 mg/kg and 0.33 to 1.04 mg/kg, respectively.

4.3.2. Influencing factors

With the daily consumption and occupational risks being the main mechanism for Hg exposure routes (Wang et al., 2021b), factors that affect Hg concentration in hair including smoking habit, occupation, age, and rice consumption were considered in this study. **Figure 3** showed the results of statistical analysis of these factors. The results indicated that there was no statistically significant difference in Hg concentration in hair based on smoking habits. However, there was a significant difference between landfill workers and non-landfill workers. This suggests that landfill workers are at high risk of Hg exposure due to inhalation of contaminated air, dust, and smoke when they transport, bury, and burn garbage using primitive working methods and little or no personal protection.

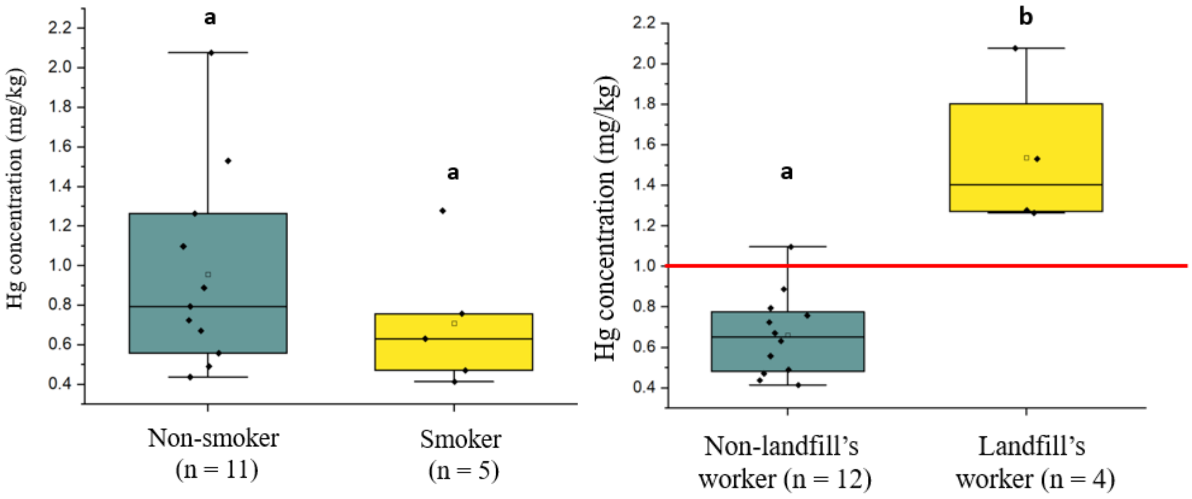


Figure 4.3. The concentrations of Hg in hair in relation to the factors, i.e. smoking habit (A), landfill's worker and non-landfill's worker (B). The same letters represent no significant difference ($p > 0.05$) and the different letters represent a significant difference ($p < 0.05$) by t-test analysis.

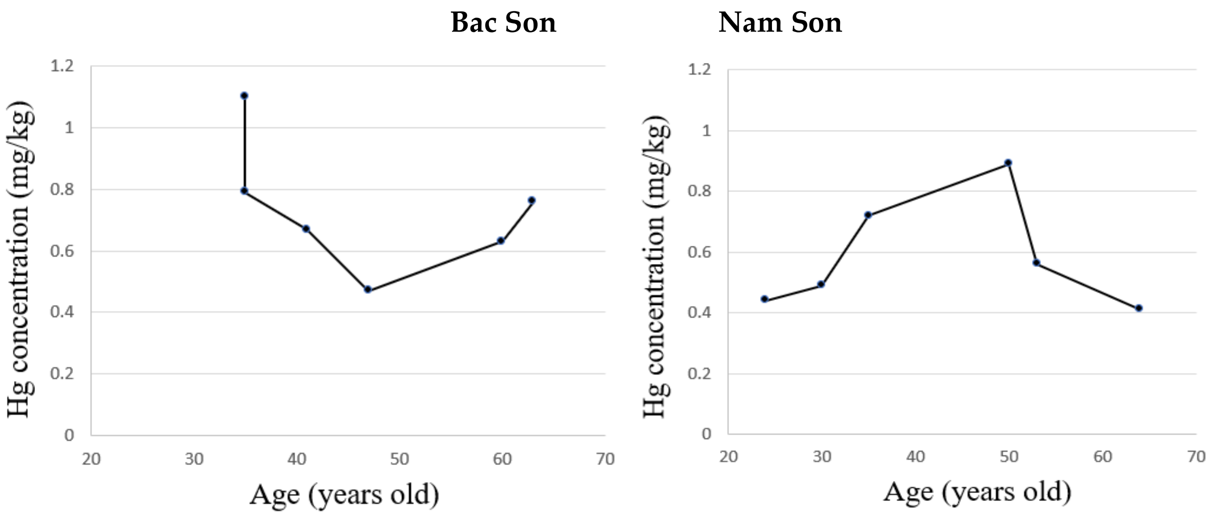


Figure 4.4. Relationship between age and Hg concentration in hair

Due to the strong influence of occupational factors on Hg concentration in hair, we performed a data analysis excluding landfill worker to assess the effect of age. **Figure 4** shows the correlation between age and Hg concentration without the influence of occupation (only non-landfill worker). There was a difference in trends between Bac Son commune and Nam Son commune. In Bac Son commune, Hg concentration in hair tends to decrease in the age group of over 20 to 50 years, then increase in the age group of 50 to over 60 years. In contrast, in Nam Son commune, Hg concentration in hair follows the opposite pattern: it tends to increase in the age group of over 20 to 50 years, then decrease in the age group of 50 to over 60 years. Xie et al., 2021 also found a similar distribution trend of Hg concentration in hair in Nam Son commune (Xie et al., 2021). This may be due to the gradual accumulation and less excretion among the young adults, enhancing body burden of Hg with increasing age. However, as for the older people, the Hg intake rate was equal or less than the excretion rate, resulting in lower accumulation (Airey, 1983). Additionally, Hg concentration in hair is influenced by various factors such as height, weight, fish intake, type of food consumed and individual excretion systems. These factors may explain the opposite trend observed in the distribution of Hg in hair in Bac Son commune.

4.3.3. Rice consumption frequency

Based on the questionnaire survey, the source of rice consumed comes from paddy fields surrounding the Nam Son landfill. The participating volunteers were divided into two different groups to evaluate the impact of rice consumption on Hg concentration in hair: low (3 bowls/day) and high (> 3 bowls/day). The results obtained showed that the average Hg concentrations in hair for these two groups were 0.63 mg/kg and 0.99 mg/kg, respectively (**Figure 5**). Four out of five participants in the low-consumption group (3 bowls/day) had hair Hg concentrations below the safety limit (1 mg/kg). In general, those in the low-consumption group had lower structural Hg levels than those in the high-consumption group. However, there was no statistically significant difference between the two groups in terms of hair Hg concentrations ($p > 0.05$).

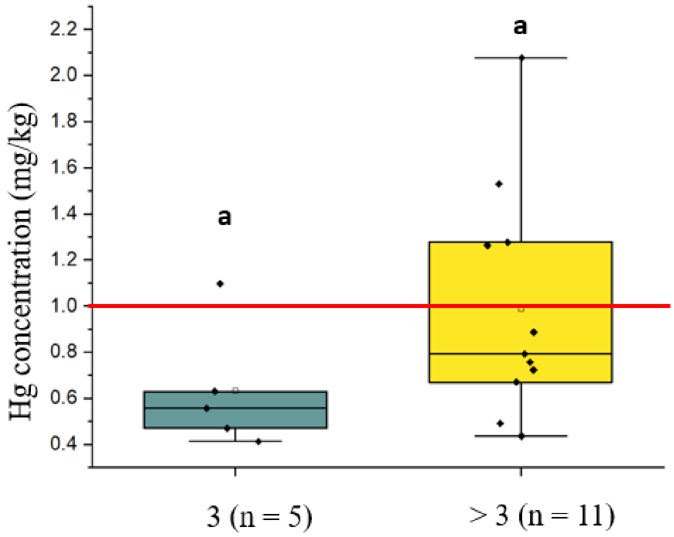


Figure 4.5. The concentrations of Hg in hair in relation to the rice consumption. The same letters represent no significant difference ($p > 0.05$) and the different letters represent a significant difference ($p < 0.05$) by t-test analysis.

Individuals' absorption and excretion mechanism differ, making it challenging to determine whether rice consumption affects Hg concentration. Several factors, including the nature of occupational activities, exposure pathways, individual behavior, biological variability, may also account for differences Hg concentration in hair.

4.4. Conclusion

This study investigated the Hg concentration in the human hair in the area around the Nam Son landfill. It also evaluated several factors affecting the concentration of Hg in hair. The average Hg concentration in hair was lower than the safety limit of 1 mg/kg recommended by WHO. However, all hair samples from landfill workers exceeded the safety standards, demonstrating that the Nam Son landfill is the main source of Hg pollution in this area, and landfill workers have high risk of Hg exposure during work. Factors such as age, smoking habits and rice consumption were found to have no significant association with Hg accumulation in hair as indicated by the data in this study. This indicates that rice is not the dominant Hg exposure route. Other food sources, such as fish, meats, or other grains need to be considered to determine the most significant factor in the food chain influencing hair Hg concentration among residents in this area for subsequent studies.

Chapter 5: General Conclusions

5.1. Summary

The study evaluated risks of Hg to humans and the environment using selected landfill area around Nam Son landfill, Hanoi, Vietnam. The risks of Hg covered **1.** Soil in the paddy fields surrounding the Nam Son landfill was contaminated with Hg originating from sources within the landfill, **2.** Rice cultivated in this area accumulates a certain amount of Hg. However, the risk of health effects from daily consumption for the residents is not high. Nonetheless, rice products used in livestock production such as rice bran used for chicken feed, require more attention due to the high risk of Hg accumulation in chickens, and **3.** The Hg concentration in the hair of individuals in the area around the landfill is relatively high, especially among landfill workers.

The spatial and seasonal distribution of Hg in soil is influenced by the physical factors such as monsoons, precipitation regime. Heavy rainfall in the rainy season increases the evaporation of Hg, leading to the amount of Hg in soil in the rainy season tending to be lower than in the dry season. SOM has a positive correlation with the amount of Hg in both soil layers ($p < 0.05$).

For brown rice samples near landfill or highway tend to have higher Hg concentrations than sites farther away. This result indicates that activities related to traffic and construction sites may play an important role in the dispersion of Hg in the study area. HQ was calculated to assess the potential health risk of Hg in this study. HQ values of male and female all were less than one, it demonstrated a relatively low risk of Hg ingestion cause by rice consumption planted in paddy fields around Nam Son landfill.

The distribution of Hg concentration in rice plants was observed to be highest in the rice roots, followed by rice shoots, rice husks, and rice grains, respectively. Additionally, the Hg concentration in rice roots showed a positive correlation with the Hg concentration in the soil in this area. Factors such as age, smoking habits and rice consumption were found no association with Hg accumulation in hair in this study. This indicates that rice is not the dominant Hg exposure route. Other food sources, such as fish, meats, or other grains need to be considered to determine the most significant factor in the food chain influencing hair Hg concentration among residents in this area for subsequent studies.

5.2. Recommendations

- Landfills are complex sources of pollution, potentially releasing mercury into the surrounding areas. It is necessary to establish and implement effective landfill management policies.
- Sorting, reducing, and recycling waste at the source constitutes the initial crucial step, enabling subsequent waste treatment measures to yield optimal results. Local authorities should conduct awareness campaigns to educate the public about waste classification, specifically, and environmental protection.
- Currently, in Nam Son landfill, the waste power plant has begun operating, and manual waste burning activities continue to take place. Monthly air monitoring in the surrounding area is essential for promptly managing and assessing their environment impact.

- Landfill workers are directly exposed to pollution sources from landfills, placing them at a high risk of Hg exposure. Measure to protect landfill workers should be implemented, including the use of personal protective equipment during work, and regular health check-ups every six months.

References

Abdullah, N. (2020). Mercury in the Diet, Absorption and Bioaccessibility. *OALib*, *07*(10), 1–15. https://doi.org/10.4236/oalib.1106666

Addai-Arhin, S., Novirsa, R., Jeong, H. H., Phan, Q. D., Hirota, N., Ishibashi, Y., Shiratsuchi, H., & Arizono, K. (2022). The human health risks assessment of mercury in soils and plantains from farms in selected artisanal and small-scale gold mining communities around Obuasi, Ghana. *Journal of Applied Toxicology*, *42*(2), 258–273. https://doi.org/10.1002/jat.4209

Ahmad, N. I., Mahiyuddin, W. R. W., Azmi, W. N. F. W., Azlee, R. S. R., Shaharudin, R., & Sulaiman, L. H. (2022). Exposure Assessment of methyl mercury from consumption of fish and seafood in Peninsular Malaysia. *Environmental Science and Pollution Research*, *29*(17), 24816–24832. https://doi.org/10.1007/s11356-021-17483-6

Airey, D. (1983). Mercury in Human Hair Due to Environment and Diet: A Review. In *Environmental Health Perspectives* (Vol. 52).

Andrews, W. J., Masoner, J. R., & Cozzarelli, I. M. (2011). *Ground Water Monitoring & Remediation Emerging Contaminants at a Closed and an Operating Landfill in Oklahoma*. https://doi.org/10.1111/j1745-6592.2011.01373.x

Ao, M., Xu, X., Wu, Y., Zhang, C., Meng, B., Shang, L., Liang, L., Qiu, R., Wang, S., Qian, X., Zhao, L., & Qiu, G. (2020). Newly deposited atmospheric mercury in a simulated rice ecosystem in an active mercury mining region: High loading, accumulation, and availability. *Chemosphere*, *238*. https://doi.org/10.1016/j.chemosphere.2019.124630

Ashfold, M. J., Latif, M. T., Samah, A. A., Mead, M. I., & Harris, N. R. P. (2017). Influence of Northeast Monsoon cold surges on air quality in Southeast Asia. *Atmospheric Environment*, *166*, 498–509. https://doi.org/10.1016/j.atmosenv.2017.07.047

Aslam, M. W., Ali, W., Meng, B., Abrar, M. M., Lu, B., Qin, C., Zhao, L., & Feng, X. (2020). Mercury contamination status of rice cropping system in Pakistan and associated health risks. *Environmental Pollution*, *263*. https://doi.org/10.1016/j.envpol.2020.114625

Atuahene, C. C., Donkoh, A., & Ntim, I. (n.d.). *Blend of oil palm slurry and rice bran as feed ingredient for broiler chickens*.

Barletta, M., Lucena, L. R. R., Costa, M. F., Barbosa-Cintra, S. C. T., & Cysneiros, F. J. A. (2012). The interaction rainfall vs. weight as determinant of total mercury concentration in fish from a tropical estuary. *Environmental Pollution*, *167*, 1–6. https://doi.org/10.1016/j.envpol.2012.03.033

Beal, S. A., Kelly, M. A., Stroup, J. S., Jackson, B. P., Lowell, T. V., & Tapia, P. M. (2014). Natural and anthropogenic variations in atmospheric mercury deposition during the Holocene near Quelccaya Ice Cap, Peru. *Global Biogeochemical Cycles*, *28*(4), 437–450. https://doi.org/10.1002/2013GB004780

Bhan, A., & Sarkar, N. N. (2005). Mercury in the Environment: Effect on Health and Reproduction. In *REVIEWS ON ENVIRONMENTAL HEALTH* (Vol. 20, Issue 1).

Bolaños-Álvarez, Y., Alonso-Hernández, C. M., Morabito, R., Díaz-Asencio, M., Pinto, V., & Gómez-Batista, M. (2016). Mercury contamination of riverine sediments in the vicinity of a mercury cell chlor-alkali plant in Sagua River, Cuba. *Chemosphere*, *152*, 376–382. https://doi.org/10.1016/j.chemosphere.2016.03.025

Bortey-Sam, N., Nakayama, S. M. M., Akoto, O., Ikenaka, Y., Fobil, J. N., Baidoo, E., Mizukawa, H., & Ishizuka, M. (2015). Accumulation of heavy metals and metalloid in foodstuffs from agricultural soils around Tarkwa area in Ghana, and associated human health risks. *International Journal of Environmental Research and Public Health*, *12*(8), 8811–8827. https://doi.org/10.3390/ijerph120808811

Braaten, H. F. V., & de Wit, H. A. (2016). Effects of disturbance and vegetation type on total and methylmercury in boreal peatland and forest soils. *Environmental Pollution*, *218*, 140–149. https://doi.org/10.1016/j.envpol.2016.08.029

Broussard, L. A., Hammett-Stabler, C. A., Winecker, R. E., & Ropero-Miller, J. D. (n.d.). *The Toxicology of Mercury*. https://academic.oup.com/labmed/article-abstract/33/8/614/2657245

Cariccio, V. L., Samà, A., Bramanti, P., & Mazzon, E. (2019). Mercury Involvement in Neuronal Damage and in Neurodegenerative Diseases. In *Biological Trace Element Research* (Vol. 187, Issue 2, pp. 341–356). Humana Press Inc. https://doi.org/10.1007/s12011-018-1380-4

Carvalho, C. M. L., Chew, E. H., Hashemy, S. I., Lu, J., & Holmgren, A. (2008). Inhibition of the human thioredoxin system: A molecular mechanism of mercury toxicity. *Journal of Biological Chemistry*, *283*(18), 11913–11923.

https://doi.org/10.1074/jbc.M710133200

Chang, C. Y., Yu, H. Y., Chen, J. J., Li, F. B., Zhang, H. H., & Liu, C. P. (2014). Accumulation of heavy metals in leaf vegetables from agricultural soils and associated potential health risks in the Pearl River Delta, South China. *Environmental Monitoring and Assessment*, *186*(3), 1547–1560. https://doi.org/10.1007/s10661-013-3472-0

Chen, L., Liu, M., Xu, Z., Fan, R., Tao, J., Chen, D., Zhang, D., Xie, D., & Sun, J. (2013). Variation trends and influencing factors of total gaseous mercury inthe Pearl River Delta-A highly industrialised region in South Chinainfluenced by seasonal monsoons. *Atmospheric Environment*, *77*, 757–766. https://doi.org/10.1016/j.atmosenv.2013.05.053

Chu, D. B., Duong, H. T., Nguyet Luu, M. T., Vu-Thi, H. A., Ly, B. T., & Loi, V. D. (2021). Arsenic and Heavy Metals in Vietnamese Rice: Assessment of Human Exposure to These Elements through Rice Consumption. *Journal of Analytical Methods in Chemistry*, *2021*. https://doi.org/10.1155/2021/6661955

Clarkson, T. W., & Clarkson, T. W. (1997). Critical Reviews in Clinical h b O r Q ? O r The Toxicology of Mercury. In *Sciences* (Vol. 34, Issue 3).

Dastoor, A. P., & Larocque, Y. (2004). Global circulation of atmospheric mercury: A modelling study. *Atmospheric Environment*, *38*(1), 147–161. https://doi.org/10.1016/j.atmosenv.2003.08.037

de Campos, R. M. L., Hierro, E., Ordóñez, J. A., Bertol, T. M., Terra, N. N., & de la Hoz, L. (2007). Fatty acid and volatile compounds from salami manufactured with yerba mate (Ilex paraguariensis) extract and pork back fat and meat from pigs fed on diets with partial replacement of maize with rice bran. *Food Chemistry*, *103*(4), 1159–1167. https://doi.org/10.1016/j.foodchem.2006.10.018

Dolbec, J., Mergler, D., Larribe, F., Roulet, M., Lebel, J., & Lucotte, M. (2001). Sequential analysis of hair mercury levels in relation to fish diet of an Amazonian population, Brazil. In *The Science of the Total Environment* (Vol. 271).

Duc, T. A., Vachaud, G., Bonnet, M. P., Prieur, N., Loi, V. D., & Anh, L. L. (2007). Experimental investigation and modelling approach of the impact of urban wastewater on a tropical river; a case study of the Nhue River, Hanoi, Viet Nam. *Journal of Hydrology*, *334*(3–4), 347–358. https://doi.org/10.1016/j.jhydrol.2006.10.022

Du, H., Guo, P., Wang, T., Ma, M., & Wang, D. (2021). Significant bioaccumulation and biotransformation of methyl mercury by organisms in rice paddy ecosystems: A potential health risk to humans. *Environmental Pollution*, *273*. https://doi.org/10.1016/j.envpol.2021.116431

Du, Z., Wu, Z., & Huang, Z. (2019). Bioaccessibility and health risk of mercury in rice of nonmercury contaminated sites using an in vitro method. *Environmental Engineering Science*, *36*(4), 413–419. https://doi.org/10.1089/ees.2018.0255

Dziok, T., Kołodziejska, E. K., & Kołodziejska, E. L. (2020). Mercury content in woody biomass and its removal in the torrefaction process. *Biomass and Bioenergy*, *143*(June). https://doi.org/10.1016/j.biombioe.2020.105832

Fao. (2018). *www.fao.org/economic/RMM Rice-Network@fao.org*. www.fao.org/economic/RMM

Fernandes Azevedo, B., Barros Furieri, L., Peçanha, F. M. I., Wiggers, G. A., Frizera Vassallo, P., Ronacher Simões, M., Fiorim, J., Rossi De Batista, P., Fioresi, M., Rossoni, L., Stefanon, I., Alonso, M. J., Salaices, M., & Valentim Vassallo, D. (2012). Toxic effects of mercury on the cardiovascular and central nervous systems. In *Journal of Biomedicine and Biotechnology* (Vol. 2012). https://doi.org/10.1155/2012/949048

Foreign Agricultural Service Global Market Analysis International Production Assessment Division. (2020).

Gabriel, M. C., Williamson, D. G., & Brooks, S. (2011). Potential impact of rainfall on the air-surface exchange of total gaseous mercury from two common urban ground surfaces. *Atmospheric Environment*, *45*(9), 1766–1774. https://doi.org/10.1016/j.atmosenv.2010.11.035

Giang, N. V., Kochanek, K., Vu, N. T., & Duan, N. B. (2018). Landfill leachate assessment by hydrological and geophysical data: case study NamSon, Hanoi, Vietnam. *Journal of Material Cycles and Waste Management*, *20*(3), 1648–1662. https://doi.org/10.1007/s10163-018-0732-7

Gibb, H., & O'Leary, K. G. (2014). Mercury exposure and health impacts among individuals in the artisanal and small-scale gold mining community: A comprehensive review. In *Environmental Health Perspectives* (Vol. 122, Issue 7, pp. 667–672). Public Health Services, US Dept of Health and Human Services. https://doi.org/10.1289/ehp.1307864

Global mercury supply, trade and demand. (n.d.). www.unep.org/chemicalsandwaste/resources/publications

Hamann, C. R., Boonchai, W., Wen, L., Sakanashi, E. N., Chu, C. Y., Hamann, K., Hamann, C. P., Sinniah, K., & Hamann, D. (2014). Spectrometric analysis of mercury content in 549 skin-lightening products: Is mercury toxicity a hidden global health hazard? *Journal of the American Academy of Dermatology*, *70*(2), 281-287.e3. https://doi.org/10.1016/j.jaad.2013.09.050

Hanoi. Minamata Convention Initial Assessment in Vietnam (Vietnam MIA Project); FINAL REPORT; The Global Environment Facility: Washington, DC, USA, 2017

Harada, M. (1995). Minamata Disease: Methylmercury Poisoning in Japan Caused by Environmental Pollution. In *Critical Reviews in Toxicology* (Vol. 25, Issue 1).

He, C., Arizono, K., Ji, H., Yakushiji, Y., Zhang, D., Huang, K., & Ishibashi, Y. (2018). Spatial distribution characteristics of mercury in the soils and native earthworms (Bimastos parvus) of the leachate-contaminated zone around a traditional landfill. *Science of the Total Environment*, *636*, 1565–1576. https://doi.org/10.1016/j.scitotenv.2018.04.259

Hoai, S. T., Lan, H. N., Viet, N. T. T., Hoang, G. N., & Kawamoto, K. (2021). Characterizing seasonal variation in landfill leachate using leachate pollution index (LPI) at nam son solid waste landfill in Hanoi, Vietnam. *Environments - MDPI*, *8*(3), 1–11. https://doi.org/10.3390/environments8030017

Horowitz, H. M., Jacob, D. J., Amos, H. M., Streets, D. G., & Sunderland, E. M. (2014). Historical mercury releases from commercial products: Global environmental implications. *Environmental Science and Technology*, *48*(17), 10242–10250. https://doi.org/10.1021/es501337j

Horvat, M., Nolde, N., Fajon, V., Jereb, V., Logar, M., Lojen, S., Jacimovic, R., Falnoga, I., Liya, Q., Faganeli, J. and Drobne, D. (2003): Total mercury, methylmercury and selenium in mercury polluted areas in the province Guizhou, China. Sci. Total Environ., 304, 231-256.

Huang, Y., Li, F., Yi, J., Yan, H., He, Z., & Li, X. (2022). *Transcriptomic and Physio-Biochemical Features in Rice (Oryza sativa L.) in Response to Mercury Stress*.

Jabłońska-Trypuć, A., Wydro, U., Wołejko, E., Pietryczuk, A., Cudowski, A., Leszczyński, J., Rodziewicz, J., Janczukowicz, W., & Butarewicz, A. (2021). Potential toxicity of leachate from the municipal landfill in view of the possibility of their migration to the environment through infiltration into groundwater. *Environmental Geochemistry and Health*, *43*(9), 3683–3698. https://doi.org/10.1007/s10653-021-00867-5

Kim, K. H., Kabir, E., & Jahan, S. A. (2016). A review on the distribution of Hg in the environment and its human health impacts. In *Journal of Hazardous Materials* (Vol. 306, pp. 376–385). Elsevier B.V. https://doi.org/10.1016/j.jhazmat.2015.11.031

Kim, K.-H., Kim, M.-Y., & Lee, G. (2001). The soil}air exchange characteristics of total gaseous mercury from a large-scale municipal land"ll area. In *Atmospheric Environment* (Vol. 35).

Kodamatani, H., Maeda, C., Balogh, S. J., Nollet, Y. H., Kanzaki, R., & Tomiyasu, T. (2017). The influence of sample drying and storage conditions on methylmercury determination in soils and sediments. *Chemosphere, 173,* 380–386. https://doi.org/10.1016/j.chemosphere.2017.01.053

Lewis, D. B., Brown, J. A., & Jimenez, K. L. (2014). Effects of flooding and warming on soil organic matter mineralization in Avicennia germinans mangrove forests and Juncus roemerianus salt marshes. *Estuarine, Coastal and Shelf Science*, *139*, 11–19. https://doi.org/10.1016/j.ecss.2013.12.032

Liberda, E. N., Tsuji, L. J. S., Martin, I. D., Ayotte, P., Dewailly, E., & Nieboer, E. (2014). The complexity of hair/blood mercury concentration ratios and its implications. *Environmental Research*, *134*, 286–294. https://doi.org/10.1016/j.envres.2014.08.007

Lin, H., Santa-Rios, A., Barst, B. D., Basu, N., & Bayen, S. (2019). Occurrence and bioaccessibility of mercury in commercial rice samples in Montreal (Canada). *Food and Chemical Toxicology*, *126*, 72–78. https://doi.org/10.1016/j.fct.2019.02.006

Li, Q., Tang, L., Qiu, G., & Liu, C. (2020). Total mercury and methylmercury in the soil and vegetation of a riparian zone along a mercury-impacted reservoir. *Science of the Total Environment*, *738*(116), 139794. https://doi.org/10.1016/j.scitotenv.2020.139794

Liu, B., Tian, K., He, Y., Hu, W., Huang, B., Zhang, X., Zhao, L., & Teng, Y. (2022). Dominant roles of torrential floods and atmospheric deposition revealed by quantitative source apportionment of potentially toxic elements in agricultural soils around a historical mercury mine, Southwest China. *Ecotoxicology and Environmental Safety*, *242*. https://doi.org/10.1016/j.ecoenv.2022.113854

Liu, M., Zhang, Q., Cheng, M., He, Y., Chen, L., Zhang, H., Cao, H., Shen, H., Zhang, W., Tao, S., & Wang, X. (2019). Rice life cycle-based global mercury biotransport and human methylmercury exposure. *Nature Communications*, *10*(1). https://doi.org/10.1038/s41467-019-13221-2

Liu, S., Wang, X., Guo, G., & Yan, Z. (2021). Status and environmental management of soil mercury pollution in China: A review. *Journal of Environmental Management*, *277*(September 2020), 111442. https://doi.org/10.1016/j.jenvman.2020.111442

Li, Y., Zhang, F., Yang, M., Zhang, J., & Xie, Y. (2019). Impacts of biochar application rates and particle sizes on runoff and soil loss in small cultivated loess plots under simulated rainfall. *Science of the Total Environment*, *649*, 1403–1413. https://doi.org/10.1016/j.scitotenv.2018.08.415

Loo, Y. Y., Billa, L., & Singh, A. (2015). Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia.

Geoscience Frontiers, *6*(6), 817–823. https://doi.org/10.1016/j.gsf.2014.02.009

Luo, Q., Ren, Y., Sun, Z., Li, Y., Li, B., Yang, S., Zhang, W., Hu, Y., & Cheng, H. (2021). Atmospheric mercury pollution caused by fluorescent lamp manufacturing and the associated human health risk in a large industrial and commercial city. *Environmental Pollution*, *269*. https://doi.org/10.1016/j.envpol.2020.116146

Mergler, D., Anderson, H. A., Chan, L. H. M., Mahaffey, K. R., Murray, M., Sakamoto, M., & Stern, A. H. (2007). Methylmercury exposure and health effects in humans: A worldwide concern. *Ambio*, *36*(1), 3–11. https://doi.org/10.1579/0044-7447(2007)36[3:MEAHEI]2.0.CO;2

Morosini, C., Terzaghi, E., Raspa, G., Zanardini, E., Anelli, S., Armiraglio, S., Petranich, E., Covelli, S., & Di Guardo, A. (2021). Mercury vertical and horizontal concentrations in agricultural soils of a historically contaminated site: Role of soil properties, chemical loading, and cultivated plant species in driving its mobility. *Environmental Pollution*, *285*. https://doi.org/10.1016/j.envpol.2021.117467

Nguyen, M. N., Dultz, S., Picardal, F., Bui, A. T. K., Pham, Q. V., Dam, T. T. N., Nguyen, C. X., Nguyen, N. T., & Bui, H. T. (2016). Simulation of silicon leaching from flooded rice paddy soils in the Red River Delta, Vietnam. *Chemosphere*, *145*, 450–456. https://doi.org/10.1016/j.chemosphere.2015.11.104

Novirsa, R., Dinh, Q. P., Jeong, H., Addai-Arhin, S., Cahya Nugraha, W., Hirota, N., Wispriyono, B., Ishibashi, Y., & Arizono, K. (n.d.). *The dietary intake of mercury from rice and human health risk in artisanal small-scale gold mining area, Indonesia*.

http://www.fundtoxicolsci.org/index_e.html

Peng, H., Reid, M. S., & Le, X. C. (2015). Consumption of rice and fish in an electronic waste recycling area contributes significantly to total daily intake of mercury. *Journal of Environmental Sciences (China)*, *38*, 83–86. https://doi.org/10.1016/j.jes.2015.10.003

QCVN 03:2023/BTNMT; National Technical Regulation on Soil Quality. The Ministry of Natural Resources and Environment (MONRE): Hanoi, Vietnam, 2023. Available online: https://datafiles.chinhphu.vn/cpp/files/vbpq/2023/3/01-btnmt-qc03.pdf (accessed on 28 January 2024). (In Vietnamese)

QCVN 8-2:2011/BYT. Hanoi, (2011): National Technical Regulation on the Limits of Heavy Metals Contamination in Food. (In Vietnamese).

Qiu, G., Feng, X., Li, P., Wang, S., Li, G., Shang, L., & Fu, X. (2008). Methylmercury accumulation in rice (Oryza sativa L.) grown at abandoned mercury mines in Guizhou, China. *Journal of Agricultural and Food Chemistry*, *56*(7), 2465–2468. https://doi.org/10.1021/jf073391a

Quynh, N. T., Jeong, H., Elwaleed, A., Ishibashi, Y., & Arizono, K. (2024). The health risk assessment of mercury in rice from paddy fields around Nam Son landfill, Hanoi, Vietnam. *Fundamental Toxicological Sciences*, *11*(3), 99–108. https://doi.org/10.2131/fts.11.99

Raghavan, S. V., Vu, M. T., & Liong, S. Y. (2017). Ensemble climate projections of mean and extreme rainfall over Vietnam. *Global and Planetary Change*, *148*, 96–104. https://doi.org/10.1016/j.gloplacha.2016.12.003

Rosniyana, A., Hashifah, M., Shariffah Norin, S., Ahmad, R., Mohd Ali, H., & Norin Syed Abdullah, S. (2009). Nutritional content and storage stability of stabilised rice bran-MR 220. In *J. Trop. Agric. and Fd. Sc* (Vol. 37, Issue 2).

Sakata, M., & Marumoto, K. (2005). Wet and dry deposition fluxes of mercury in Japan. *Atmospheric Environment*, *39*(17), 3139–3146. https://doi.org/10.1016/j.atmosenv.2005.01.049

Saldaña-Villanueva, K., Pérez-Vázquez, F. J., Ávila-García, I. P., Méndez-Rodríguez, K. B., Carrizalez-Yáñez, L., Gavilán-García, A., Vargas-Morales, J. M., Van-Brussel, E., & Diaz-Barriga, F. (2022). A preliminary study on health impacts of Mexican mercury mining workers in a context of precarious employment. *Journal of Trace Elements in Medicine and Biology*, *71*. https://doi.org/10.1016/j.jtemb.2022.126925

Siedlikowski, M., Bradley, M., Kubow, S., Goodrich, J. M., Franzblau, A., & Basu, N. (2016). Bioaccessibility and bioavailability of methylmercury from seafood commonly consumed in North America: In vitro and epidemiological studies. *Environmental Research*, *149*, 266–273. https://doi.org/10.1016/j.envres.2016.02.013

Srogi, K. (2007). *Mercury Content of Hair in Different Populations Relative to Fish Consumption*.

Suárez-Criado, L., Rodríguez-González, P., Marrugo-Negrete, J., García Alonso, J. I., & Díez, S. (2023). Determination of methylmercury and inorganic mercury in human hair samples of individuals from Colombian gold mining regions by double spiking isotope dilution and GC-ICP-MS. *Environmental Research, 231*. https://doi.org/10.1016/j.envres.2023.115970

Tang, W., Cheng, J., Zhao, W., & Wang, W. (2015). Mercury levels and estimated total daily intakes for children and adults from an electronic waste recycling area in Taizhou, China: Key role of rice and fish consumption. *Journal of Environmental Sciences (China)*, *34*, 107–115. https://doi.org/10.1016/j.jes.2015.01.029

Tang, Z., Fan, F., Deng, S., & Wang, D. (2020). Mercury in rice paddy fields and how does some agricultural activities affect the translocation and transformation of mercury - A critical review. In *Ecotoxicology and Environmental Safety* (Vol. 202). Academic Press. https://doi.org/10.1016/j.ecoenv.2020.110950

Tan, Q., Song, Q., & Li, J. (2015). The environmental performance of fluorescent lamps in China, assessed with the LCA method. *International Journal of Life Cycle Assessment*, *20*(6), 807–818. https://doi.org/10.1007/s11367-015-0870-2

Tao, Z., Bian, R., & Chai, X. (2018). Methylmercury levels in cover soils from two landfills in Xi'an and Shanghai, China: Implications for mercury methylation potentials. *Waste Management*, *78*, 331–336. https://doi.org/10.1016/j.wasman.2018.06.008

Tchounwou, P. B., Ayensu, W. K., Ninashvili, N., & Sutton, D. (2003). Environmental exposure to mercury and its toxicopathologic implications for public health. In

Environmental Toxicology (Vol. 18, Issue 3, pp. 149–175). https://doi.org/10.1002/tox.10116

The World Bank. *Assessment of Management of Daily Waste and Hazardous Industrial Waste Options and Actions for Implementation of the National Strategy*; The World Bank: Washington, DC, USA, 2018. (In Vietnamese).

Thi Quynh, N., Jeong, H., Elwaleed, A., Nugraha, W. C., Arizono, K., Agusa, T., & Ishibashi, Y. (2024). Spatial and Seasonal Patterns of Mercury Accumulation in Paddy Soil around Nam Son Landfill, Hanoi, Vietnam. *Soil Systems*, *8*(1), 30. https://doi.org/10.3390/soilsystems8010030

Thompson, A. H., Wilson, A. S., & Ehleringer, J. R. (2013). Hair as a Geochemical Recorder: Ancient to Modern. In *Treatise on Geochemistry: Second Edition* (Vol. 14, pp. 371–393). Elsevier Inc. https://doi.org/10.1016/B978-0-08-095975-7.01227-4

Tomiyasu, T., Kodamatani, H., Imura, R., Matsuyama, A., Miyamoto, J., Akagi, H., Kocman, D., Kotnik, J., Fajon, V., & Horvat, M. (2017). The dynamics of mercury near Idrija mercury mine, Slovenia: Horizontal and vertical distributions of total, methyl, and ethyl mercury concentrations in soils. *Chemosphere*, *184*, 244–252. https://doi.org/10.1016/j.chemosphere.2017.05.123

US EPA. (US Environmental Protection Agency). (1997). *Mercury Study Report to the Congress. EPA 452/R-97-0003. US EPA, Washington, DC.*

Wang, C., Wang, Z., Gao, Y., & Zhang, X. (2021). Planular-vertical distribution and pollution characteristics of cropland soil Hg and the estimated soil–air exchange fluxes of gaseous Hg over croplands in northern China. *Environmental Research*, *195*. https://doi.org/10.1016/j.envres.2021.110810

Wang, F., Wang, S., Zhang, L., Yang, H., Wu, Q., & Hao, J. (2016). Characteristics of mercury cycling in the cement production process. *Journal of Hazardous Materials*, *302*, 27–35. https://doi.org/10.1016/j.jhazmat.2015.09.042

Wang, Y., Li, L., Yao, C., Tian, X., Wu, Y., Xie, Q., & Wang, D. (2021a). Mercury in human hair and its implications for health investigation. In *Current Opinion in Environmental Science and Health* (Vol. 22). Elsevier B.V. https://doi.org/10.1016/j.coesh.2021.100271

Wang, Y., Li, L., Yao, C., Tian, X., Wu, Y., Xie, Q., & Wang, D. (2021b). Mercury in human hair and its implications for health investigation. In *Current Opinion in Environmental Science and Health* (Vol. 22). Elsevier B.V. https://doi.org/10.1016/j.coesh.2021.100271

Wu, M., Yan, C., Xu, J., Wu, W., Li, H., & Zhou, X. (2013). Umbilical cord blood mercury levels in China. *Journal of Environmental Sciences (China)*, *25*(2), 386–392. https://doi.org/10.1016/S1001-0742(12)60061-8

Wu YS, Osman AI, Hosny M, Elgarahy AM, Eltaweil AS, Rooney DW, Chen Z, Rahim NS, Sekar M, Gopinath SCB, Mat Rani NNI, Batumalaie K, Yap PS. The Toxicity of Mercury and Its Chemical Compounds: Molecular Mechanisms and Environmental and Human Health Implications: A Comprehensive Review. ACS Omega. 2024 Jan

22;9(5):5100-5126. doi: 10.1021/acsomega.3c07047.

Xie, Q., Wang, Y., Li, S., Zhang, C., Tian, X., Cheng, N., Zhang, Y., & Wang, D. (2021). Total mercury and methylmercury in human hair and food: Implications for the exposure and health risk to residents in the Three Gorges Reservoir Region, China. *Environmental Pollution*, *282*. https://doi.org/10.1016/j.envpol.2021.117041

Xu, J., Zhang, J., Lv, Y., Xu, K., Lu, S., Liu, X., & Yang, Y. (2020). Effect of soil mercury pollution on ginger (Zingiber officinale Roscoe): Growth, product quality, health risks and silicon mitigation. *Ecotoxicology and Environmental Safety*, *195*(March), 110472. https://doi.org/10.1016/j.ecoenv.2020.110472

Yang, Y.-K., Cheng, Z., Shi, X.-J., Tao, L., & Wang, D.-Y. (2007). Effect of organic matter and pH on mercury release from soils. In *Journal of Environmental Sciences* (Vol. 19).

Yu, H., Li, J., & Luan, Y. (2018). Meta-analysis of soil mercury accumulation by vegetables. *Scientific Reports*, *8*(1). https://doi.org/10.1038/s41598-018-19519-3

Zhang, Y. C., Luo, M., Fang, X. Y., Zhang, F. Q., & Cao, M. H. (2021). Energy value of rice, broken rice, and rice bran for broiler chickens by the regression method. *Poultry Science*, *100*(4). https://doi.org/10.1016/j.psj.2020.12.069

Zhao, J. Y., Ye, Z. H., & Zhong, H. (2018). Rice root exudates affect microbial methylmercury production in paddy soils. *Environmental Pollution*, *242*, 1921–1929. https://doi.org/10.1016/j.envpol.2018.07.072

Zhu, W., Li, Z., Chai, X., Hao, Y., Lin, C. J., Sommar, J., & Feng, X. (2013a). Emission characteristics and air-surface exchange of gaseous mercury at the largest active landfill in Asia. *Atmospheric Environment*, *79*, 188–197. https://doi.org/10.1016/j.atmosenv.2013.05.083

Zhu, W., Li, Z., Chai, X., Hao, Y., Lin, C. J., Sommar, J., & Feng, X. (2013b). Emission characteristics and air-surface exchange of gaseous mercury at the largest active landfill in Asia. *Atmospheric Environment*, *79*, 188–197. https://doi.org/10.1016/j.atmosenv.2013.05.083