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Human Health Risks from Exposure to Heavy Metals of Suspended Particulate Matter around the Tongon Gold Mine, Côte d'Ivoire

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Abstract

The Tongon mine, the largest gold mine in Côte d'Ivoire, has been in operation since April 2010. However, to our knowledge to date, no study has been conducted on metallic contamination in suspended particulate matter (PM_{10} and $PM_{2.5}$) where there is a lack of information on the carcinogenic and non-carcinogenic risk to human health associated with the exposure of populations in the Tongon area to these pollutants. The general objective of this study is to evaluate the level of contamination of PM_{10}; $PM_{2.5}$ by heavy metals and their impact on the health of populations exposed to these pollutants in the Tongon gold mine area. The sampling and measurement of suspended particulate matter (PM_{10} and $PM_{2.5}$) were done using a MiniVol TAS passive air sampler. Heavy metal concentrations were determined by inductively coupled plasma mass spectroscopy (Nex ION 2000 ICP-MS, USA). The results indicate that the average concentrations of suspended particles ($PM_{2.5}$ and PM_{10}) obtained are all above the recommended exposure limits. In addition, among the heavy metals contained in the suspended particles, the concentrations of arsenic and nickel are high and all above the standard limit values. The assessment of the health risks related to the inhalation of PM_{10} particles reveals that their inhalation over a long period could cause a carcinogenic risk.

Keywords

Particulate Matters (PM_{10} and $PM_{2.5}$), West Africa, Tongon, Heavy Metals, Inhalation, Carcinogenic Risk, Metallic Contamination

1. Introduction

Populations in gold mining areas often face numerous health problems related to the emergence of toxic pollutants including heavy metals [1] [2]. Environmental heavy metal contamination from gold mining areas has been identified as one of the most serious environmental problems in many countries [3]. This is because mining, ore processing, and tailings disposal are operations that cause environmental contamination through the dispersion of heavy metals [3] [4]. In gold mining areas, heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), nickel (Ni), and lead (Pb) accumulate in dust and can pose health risks to people living near these mining areas [5]. In addition, inhalation of heavy metals from particles with aerodynamic diameters less than 10 µm is increasingly recognized as an important exposure pathway associated with potentially harmful human health outcomes [6] [7]. Elevated metal concentrations in PM_{10} are often reported near industrial mining sites [8] [9]. In Italy, manganese (Mn), nickel (Ni), zinc (Zn), chromium (Cr), and iron (Fe) in PM_{10} near mining sites have recently been correlated with respiratory system impairment [10]. Studies have shown that PM_{10} inhalation has also been associated with elevated blood and urine concentrations of arsenic (As), lead (Pb), copper (Cu), and cadmium (Cd) in individuals exposed to this type of pollution [11] [12] [13].

In Côte d'Ivoire, the economy has long been based on agriculture. It is the world's largest producer of cocoa and Africa's largest exporter of coffee, rubber, and cashew nuts [13]. In recent decades, income generated from cash crops has declined significantly. In order to reduce the country's dependence on these crops and ensure economic recovery, the Ivorian government has encouraged mineral exploration and mining development [13]. As in many developing countries, mining contributes to economic growth and poverty reduction through job creation and foreign exchange earnings [14] [15]. Several licenses have been granted to gold exploration companies in recent years [14] [16]. This has led to the commissioning of several large gold mining companies across the country.

The Tongon mine, the largest gold mine in the country, has been in operation since April 2010 [14] [16]. Thus, in the mining operation: crushing (crushing and grinding), mining processes (flotation and separation), and extraction (leaching and adsorption) produced between 2012 and 2015 about 1.356 × 107 tons of ore [14]. This mine generated 8.037 × 107 tons of waste rock and 1.24 × 106 m^3 of tailings that are stored in landfills and tailings facilities (TDFs) located around the mine [14]. Mine wastes such as waste rock and slurry farm contain heavy metals [14]. These metals can be transferred to the surrounding atmosphere by precipitation and wind force [17].

Although considerable efforts have been made by the Tongon mine authorities to protect the environment and control the dispersion of contaminants, incidents have been reported at the mine [14]. These incidents are likely to promote the mobility of heavy metals in the surrounding environment [14]. In addition, studies conducted on metal contamination in the Tongon area to date have been limited to geochemistry [14]. However, no data to our knowledge to date on metal contamination in suspended particulate matter (PM_{10} and $PM_{2.5}$) is available in the literature for the Tongon area. In addition, no studies have been done to assess the carcinogenic and non-carcinogenic risks to human health associated with exposure of the surrounding populations to toxic metals. Due to the lack of data on metal contamination in suspended particulate matter, the lack of information on the carcinogenic and non-carcinogenic human health risk associated with exposure of populations in the Tongon area to these pollutants, it appeared necessary to assess metal contamination simultaneously in suspended particulate matter (PM_{10} and $PM_{2.5}$), to assess the carcinogenic and non-carcinogenic human health risk associated with exposure of surrounding populations to these metals by inhalation and dermal route.

The general objective of this study is to evaluate in the area of the Tongon gold mine, the level of contamination of PM_{10}; $PM_{2.5}$ by heavy metals and their impact on the health of the populations exposed to these pollutants. To this end, it was more specifically a question of: determining the levels of these metals in suspended particles (PM_{10} and $PM_{2.5}$); evaluating the potential health risks related to the exposure of the surrounding populations to these by inhalation.

This study established, for the first time, a database on the metallic contamination of suspended particles (PM_{10} and $PM_{2.5}$) in the Tongon area and on the carcinogenic and non-carcinogenic risks to human health associated with the exposure of the surrounding populations to heavy metals by inhalation.

2. Material and Methods

2.1. Study Area

2.1.1. Location

The Tongon gold mine, owned by Barrick Gold Corporation, is located in the Savanes district (northern Côte d'Ivoire; N9˚57' - 5˚76' W5˚42' - 13˚68'), approximately 628 km northeast of Abidjan, the economic capital, and 75 km from Korhogo, the district capital. The mine is located in the department of M'Bengué between two villages of the Tagban township, Poungbe and Tongon, and covers approximately 2000 ha of which more than 50% is occupied by vegetation.

2.1.2. Sampling and Measurement of Suspended Particles

The sampling and measurement of suspended particulates (PM_{10} and $PM_{2.5}$) was done using a MiniVol TAS passive air sampler. It is configured to collect only one type of sample: $PM_{2.5}$ and PM_{10}. This filtration sampling required the combination of several devices: a sampling head (allowing or not to select in size the incoming particles); a collection support (filter or membrane) and a pumping system. Thus, the MiniVol TAS pump draws air at a rate of 5 liters/minute through a size separator (impinger) and then through a 47 mm diameter filter. The particulate sample is trapped by the filter and must be weighed before and after sampling using a balance with an accuracy of 0.1 mg. The concentrations are expressed in μg/m^3. Sampling was carried out at fourteen points as shown in Figure 1, Figure 2 and Table 1.

Figure 1. Village sampling sites.

Figure 2. Sampling sites at the mine.

Table 1. Description of sampling sites.

Areas	Measurement points	GPS coordinates
Sampling site in the villages	TONGON village	N09˚54'22.20"/W005˚43'36.10"
	POUNGBE	N09˚54'07.2"/W005˚46'21.10"
	SEKONKAHA	N09˚54'30.80"/W005˚49'11.40"
	KATCHE	N09˚55'24.8"/W005˚42'08.6"
	KOROKARA	N09˚54'12.30"/W005˚37'46.10"
Sampling site at the mine	PIT SUD	N09˚55'30.24"/W005˚43'0.40"
	PIT NORD	N09˚56'34.30"/W005˚41'32.90"
	WATER PLANT	N09˚56'33.10"/W005˚42'37.30"
	ANCIEN CAMP	N09˚55'33.90"/W005˚43'25.90"
	AFRILOG	N09˚56'20.60"/W005˚42'33.50"
	MAIN GATE	N09˚56'02.15"/W005˚43'23.71"
	SQ 15	N09˚56'46.70"/W005˚42'29.50"
	POWER HOUSE	N09˚56'36.40"/W005˚42'19.80"
	TOMI OFFICE	N09˚55'49.70"/W005˚41'56.10"
	ZONE ELUTION	N09˚56'22.30"/W005˚42'19.10"

2.2. Determination of Total Heavy Metal Concentrations in PM_{10} and $PM_{2.5}$

The glass fiber filters are weighed to determine the mass of the deposits and then undergo mineralization. The extraction method is detailed as follows: the filter is impregnated in a beaker containing HNO_3 (20%) for 4 hours. It is rinsed with distilled water and immersed in another 100 ml beaker. A volume of 3 ml of HNO_3 is added and the beaker is then covered with a watch glass. The beaker is heated with a hot plate until evaporation at 95˚C. It is allowed to cool and a volume of 2 mL of HNO_3 is added. It is heated again until partial drying. A volume of 1 ml of HF is added to dissolve all the particles present under moderate heating until partial drying at 95˚. The beaker is allowed to cool and 10 ml of distilled water is added. The contents of the beaker are transferred to another 100 ml beaker and the volume is reduced to 100 mL with a distilled water solution containing 1% HCL and 0.7% HNO_3 at 60˚C. Finally, the solution is filtered to remove silicates and other insoluble materials. It was left to stand for 6 hours and the metals were determined by inductively coupled plasma mass spectroscopy (NexION 2000 ICP-MS, USA).

2.3. Prospective Health Risk Assessment of Heavy Metal Exposure

In this study, the carcinogenic and non-carcinogenic risk assessment models developed by the United States Environmental Protection Agency (USEPA) were used to evaluate the potential health risks to children and adults exposed to heavy metals [18]-[27].

2.3.1. Prospective Health Risk Assessment of Heavy Metal Exposure. Calculation of the Daily Exposure Dose to Heavy Metals

The different daily exposure doses to heavy metals by inhalation and dermal route were determined using the following equations [24] [27]

$$CDI_{\text{inhale}} = \frac{C \times ET \times EF \times ED}{PEF \times 24 \times AT} \tag{1}$$

$$CDI_{\text{dermal-air}} = \frac{C \times EF \times ED \times SA \times AF \times ABS \times CF}{BW \times AT} \tag{2}$$

C: metal concentrations in PM_{10} and $PM_{2.5}$;

CDI: chronic daily intake of heavy metal ($mg \cdot kg^{-1} \cdot d^{-1}$) ;

EF: frequency of exposure: 350 days/year;

ED: exposure duration: 6 years for children and 24 years for adults;

BW: body weight: 15 kg for children and 70 kg for adults;

AT: Average time for non-carcinogens: *ED* × 365 days × 24 hours/days;

AT: Average time for carcinogens: 70 years × 365 days/year ×24 hours;

SA: exposed skin area: 5700 cm^2;

AF: Water adhesion factor: 0.07 $mg \cdot cm^2$ for adults and children;

AF: Skin adhesion factor for airborne particles: 0.2 mg cm^2 for adults and children;

ABS: Fraction of cutaneous absorption: 0.03 for arsenic and 0.001 for the other heavy metals;

ET: Exposure frequency: 24 hours/day;

PEF: Particle emission factor: 1.36 × 109 $m^3 \cdot kg^{-1}$;

CF: Unit conversion factor: 10^{-6} $kg \cdot mg^{-1}$.

2.3.2. Cancer Risk Related to Long-Term Exposure to Heavy Metals

The cancer risk can be evaluated from the following equation:

$$\text{Cancer risk} = CDI \times SF \tag{3}$$

where Cancer risk represents the probability that an individual will be exposed to cancer risks during his or her lifetime as a result of prolonged exposure to heavy metals. The acceptable or tolerable risk for regulatory purposes is in the range of 10^{-6} to 10^{-4} [26] [27];

CDI: is the chronic daily intake of heavy metal ($mg \cdot kg^{-1} \cdot d^{-1}$); *SF* is the slope factor or unit risk of the carcinogenic heavy metal ($mg \cdot kg^{-1} \cdot d^{-1}$).

According to the classifications defined by the International Agency for Research on Cancer [18], arsenic, nickel, and cadmium are Class I carcinogens, lead is Class 2A, and cobalt is Class 2B [26]. However, copper, zinc, and manganese are not listed in different carcinogenic groups [18]. Therefore, their carcinogenic risks were not investigated in this study.

2.3.3. Cumulative Cancer Risk from Long-Term Exposure to Heavy Metals

The cumulative lifetime risk of developing cancer from prolonged exposure to carcinogenic heavy metals is calculated from the following equation:

$$\text{total cancer risk} = \sum_{k=1}^{n} CDI_k \times SF_k \tag{4}$$

where CDI_k is the chronic daily intake ($mg \cdot kg^{-1} \cdot d^{-1}$) of carcinogenic heavy metal k;

SF_k is the slope factor or unit risk of heavy metal k ($mg \cdot kg^{-1} \cdot d^{-1}$).

2.3.4. Non-Cancer Risk Quotient (*HQ*)

The non-cancer risk of the various heavy metals can be expressed as a hazard quotient:

$$HQ = CDI / RFD \tag{5}$$

where the non-carcinogenic risk quotient (HQ) is the ratio of the exposure to the hazardous substance CDI ($mg \cdot kg^{-1} \cdot d^{-1}$) to the chronic reference dose of the heavy metal (RFD).

2.3.5. Chronic Risk Index (*HI*)

It is calculated from the following equation

$$HI = \sum_{k=1}^{n} CDI_k / RFD_k \tag{6}$$

where the chronic risk index (HI) is the sum of risk quotients for multiple heavy metals or multiple exposure routes;

CDI_k is the daily dose of heavy metal (k) and RFD_k is the chronic reference dose for heavy metal k. HI values greater than 1 indicates that there is a possibility of a no carcinogenic risk. Conversely, HI values below indicate that there is no risk of non-cancer effects.

In this work, chronic reference doses, unit risks for heavy metals were downloaded from the USEPA website [27].

3. Results and Discussion

3.1. Heavy Metals in Suspended Particulate Matter in the Study Area

3.1.1. PM_{10} and $PM_{2.5}$ Concentrations

Figures 3-9 present the different variations of $PM_{2.5}$ and PM_{10} dust at the WATER PLANT, ANCIEN CAMP, TONGON, KOROKARA, POUNGBE, SEKONKAHA, and KATCHE sampling sites in the TONGON mine area.

For $PM_{2.5}$, the average concentrations obtained over 24 hours of measurement are 28.37; 40.85; 35.15; 34.31; 28.95; 34.46; 27.60 µg/m³ respectively for the sampling sites WATER PLANT, ANCIEN CAMP, TONGON, KOROKARA, POUNGBE, SEKONKAHA, KATCHE. These average concentrations obtained are all higher than the exposure limit recommended by the Decree N˚2017-125 of February 22, 2017 on air quality which is 25 µg/m³.

Similarly, the 24-hour average PM_{10} values for all sampling sites are all above the exposure limit recommended by Decree No. 2017-125 of February 22, 2017 on air quality, which is 50 µg/m³. They are 76.31; 79.0; 73.64; 77.91; 66.65; 62.96; 71.62 respectively for the sites WATER PLANT, ANCIEN CAMP, TONGON, KOROKARA, POUNGBE, SEKONKAHA, and KATCHE.

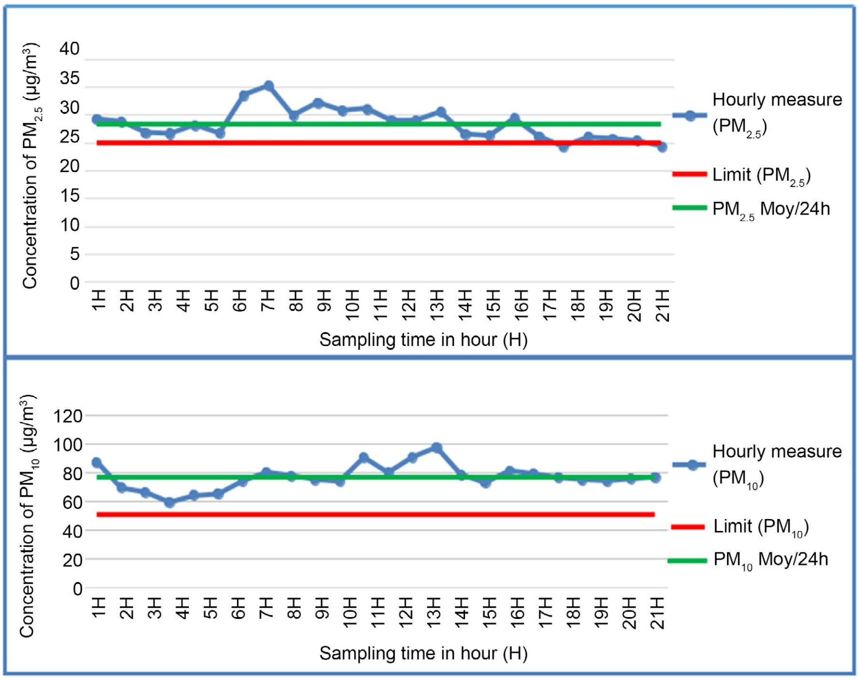

Figure 3. Variation of $PM_{2.5}$ and PM_{10} dust WATER PLANT.

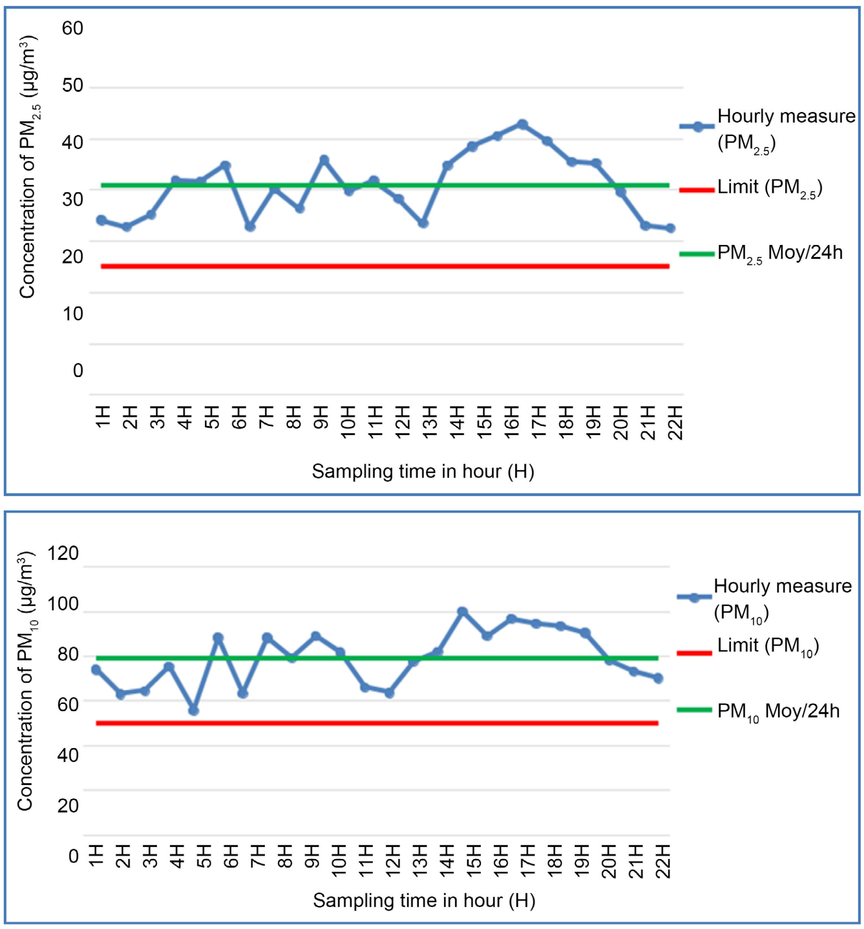

Figure 4. Variation of $PM_{2.5}$ and PM_{10} dust ANCIEN CAMP.

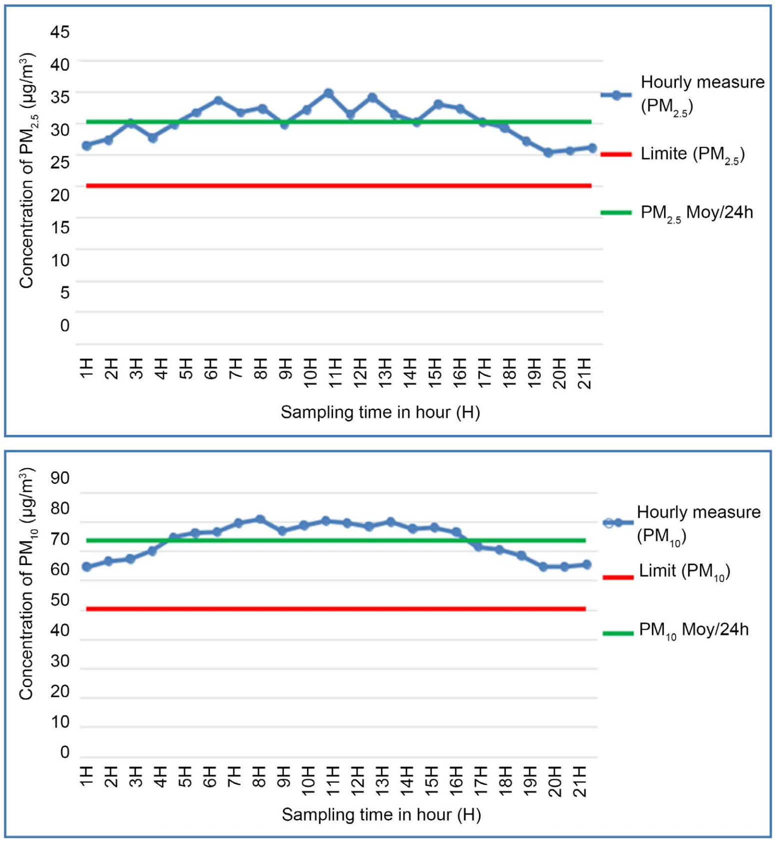

Figure 5. Variation of $PM_{2.5}$ and PM_{10} dust TONGON.

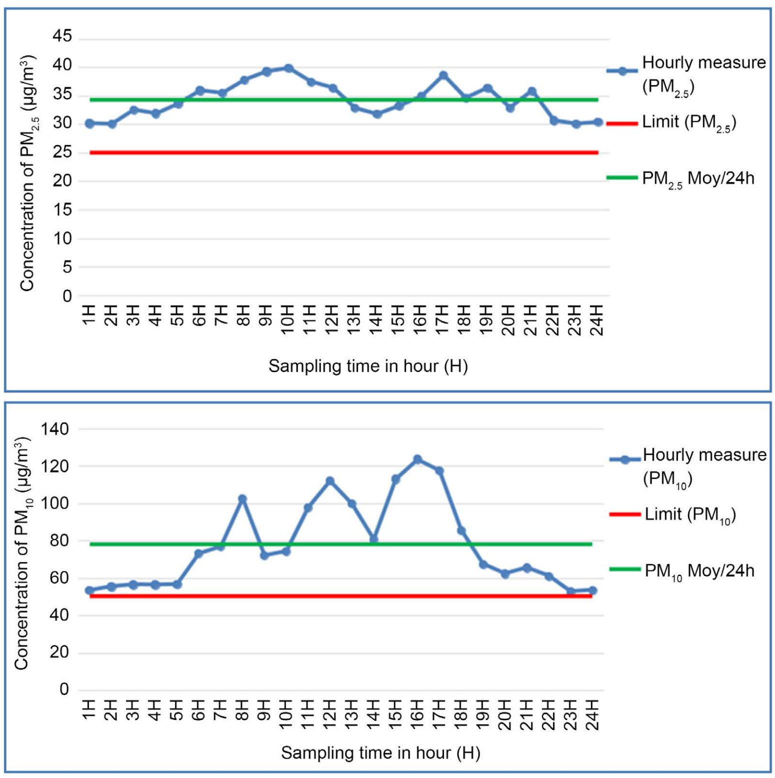

Figure 6. Variation of $PM_{2.5}$ and PM_{10} dust KOROKARA.

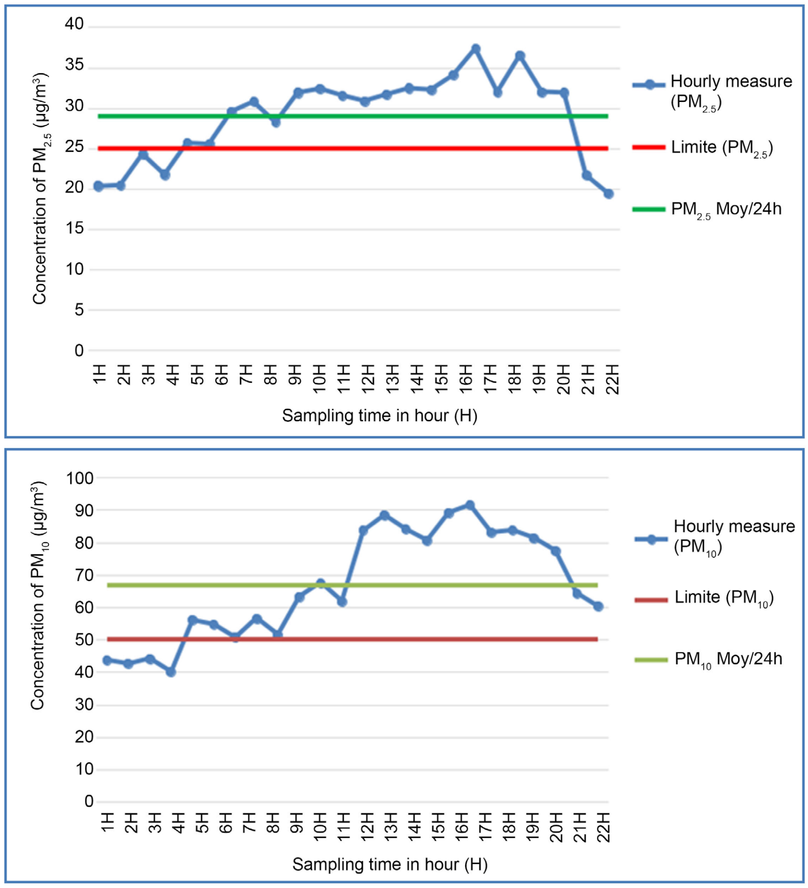

Figure 7. Variation of $PM_{2.5}$ and PM_{10} dust POUNGBE.

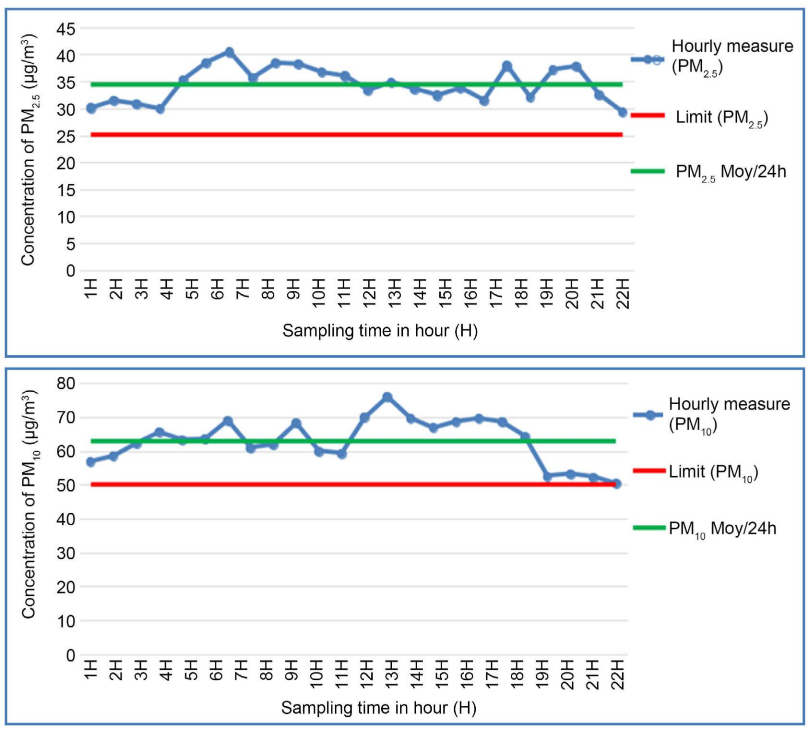

Figure 8. Variation of $PM_{2.5}$ and PM_{10} dust SEKONKAHA.

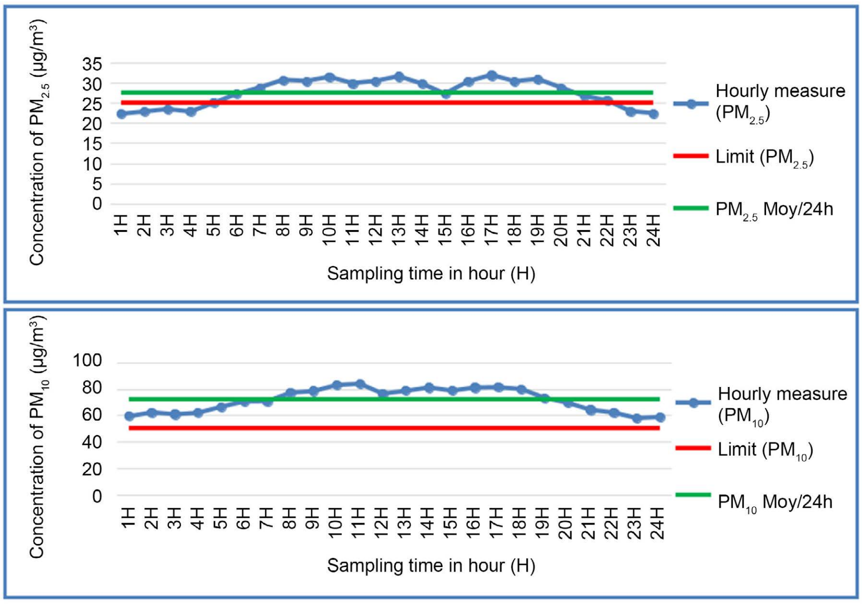

Figure 9. Variation of $PM_{2.5}$ and PM_{10} dust KATCHE.

The high PM_{10} and $PM_{2.5}$ levels in these areas are mainly related to the mine activities (ore extraction, transportation, crushing, and grinding and vehicle traffic on site). It should be remembered that particulate matter in the atmosphere from metal mine waste can have adverse health effects on people living in the vicinity for two reasons:

- First, the formation of particulate matter smaller than 10 mm in diameter generates health problems associated with both short- and long-term exposure [28].

- Second, heavy metals are recalcitrant, highly toxic, non-biodegradable, and bioaccumulative pollutants. Heavy metals coated to these particulate matter (PM_{10}) resulting from mine waste resuspension can be inhaled or ingested and these contaminants can be absorbed into the body, depending on their term bioavailability [29]. Therefore, in the following paragraph, heavy metal contents in PM_{10} particles were determined.

3.1.2. Heavy Metal Concentrations in PM_{10}

Figures 10-12 show the variation of the average heavy metal concentrations of PM_{10} at the different sampling sites.

The average concentrations vary from 0.0082 ± 0.0009 to 0.016 ± 0.006; from 0.025 ± 0.004 to 0.045 ± 0.003; from 0.031 ± 0.003 to 0.061 ± 0.002 µg/m³ respectively for the metals arsenic, nickel and lead. For the metals arsenic and nickel, they are high and all above the standard limit values, which are 0.006 µg/m³ and 0.02 µg/m³ respectively for arsenic and nickel. In contrast to arsenic and nickel, lead concentrations are very low and well below the standard limit value of 0.5 µg/m³.

The high concentrations of the metals arsenic and nickel are thought to come from automotive and industrial emissions from the mine while the low lead

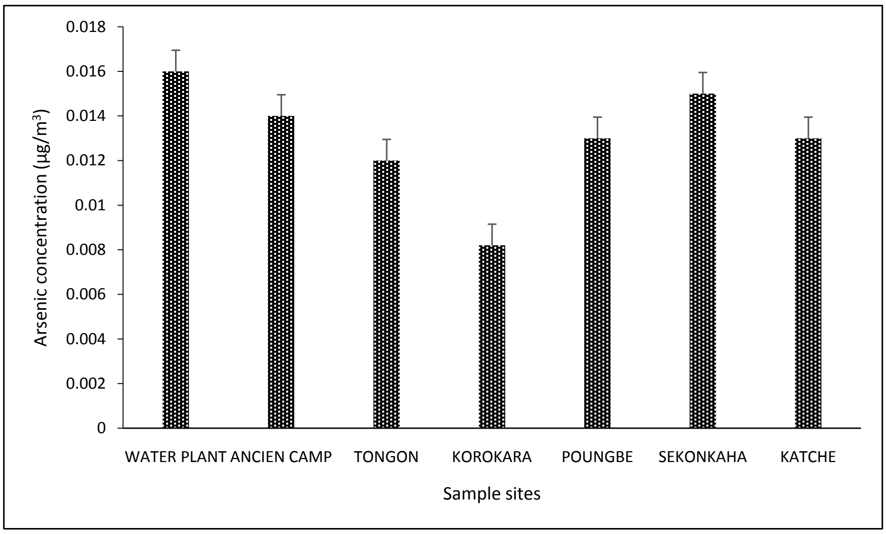

Figure 10. Arsenic concentrations in PM_{10}.

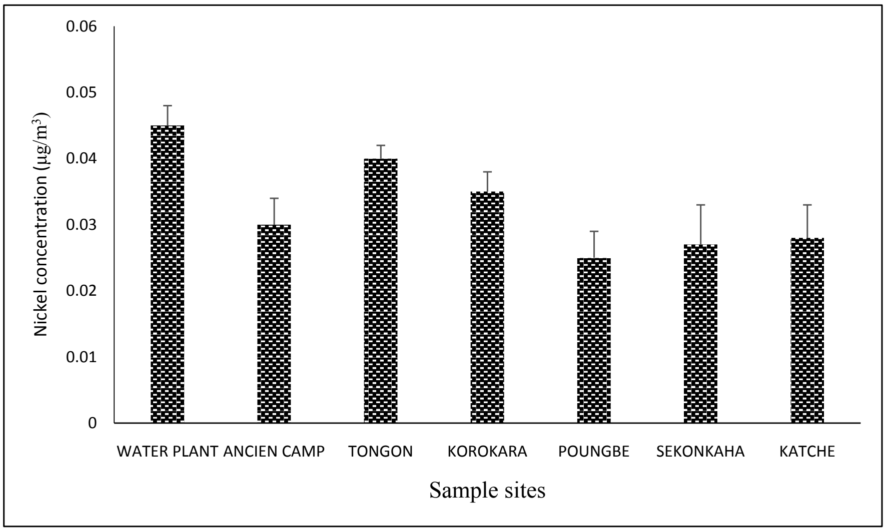

Figure 11. Nickel concentrations in PM_{10}.

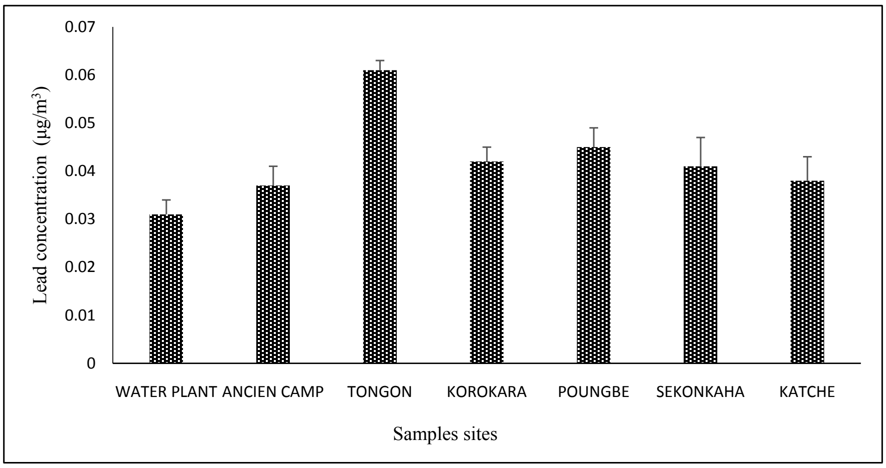

Figure 12. Lead Concentrations in PM_{10}.

concentrations are thought to be due to the uses of unleaded fuel [29]. Other metals in PM_{10} would be emitted from a variety of natural and anthropogenic sources such as crustal materials, road dust, motor vehicles, incineration, and other industrial activities [29]. It should be remembered that toxic heavy metals associated with respirable PM can cause lung and cardiopulmonary damage, cardiovascular problems, damage to various organs, and premature mortality in humans [29]. Among the metals, arsenic is a human carcinogen and can cause respiratory tract disorders, skin conditions, cardiovascular and nervous system problems. Lead interferes with normal kidney function and causes kidney disorders.

In addition, heavy metals in PM differ in concentration at different locations (**Figures 10-12**). These differences could be explained by the various contributing sources and meteorological factors [29]. Therefore, it is essential to study the health risks of metals, especially in gold mining areas, where many sources contribute to the pollutants [29].

3.2. Health Risk Assessment of Heavy Metals in Suspended Particulate Matter (PM_{10})

Due to the lack of local exposure parameters for health risk assessments, we referred to U.S. exposure parameters [30]. The exposure parameters, which were calculated under conditions of respiratory absorption, are presented in **Table 2**. As shown in **Figure 13** and **Figure 14**, the risk level for carcinogenic heavy metals for exposure through the respiratory system ranged from 1.95E-16 to 1.33E-11,

Table 2. Reaction parameters for heavy metals entering the human body through the respiratory system.

Element	Nature	SF (mg/(kg·d))
As	Carcinogenic	20.7
Ni	Carcinogenic	1.19

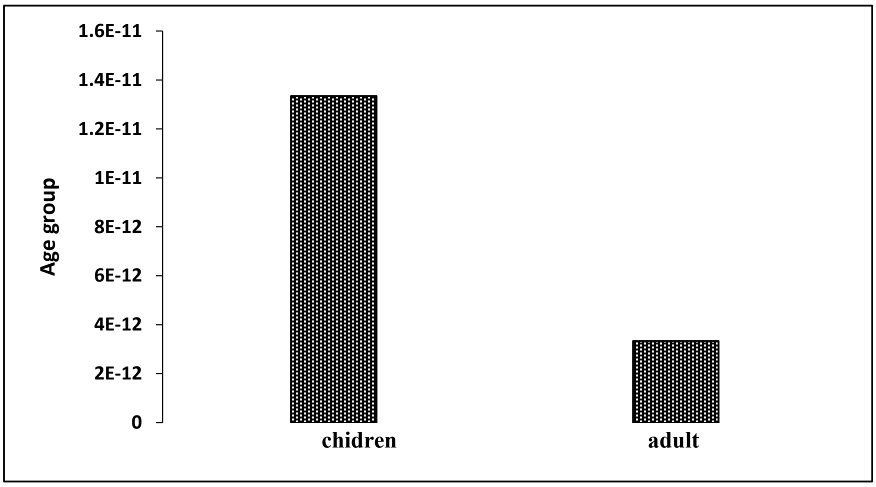

Figure 13. Cumulative cancer risk from long-term inhalation of arsenic in PM_{10}.

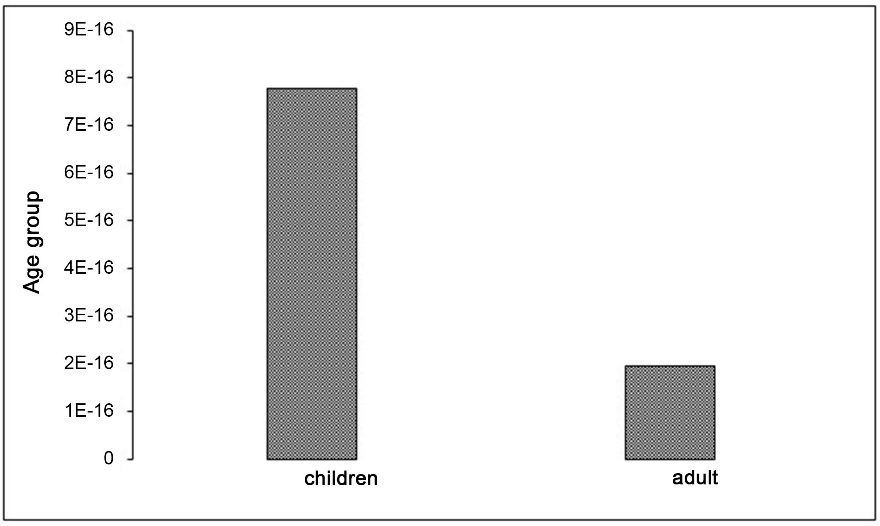

Figure 14. Cumulative cancer risk from long-term inhalation of lead in PM_{10}.

which is below the average risk acceptance level of 1×E-06/year [30]. Risk levels for carcinogenic heavy metals appeared in the following order: As > Ni. In addition, the carcinogens had the highest cancer risk for adults, followed by children. It should be emphasized that due to their physicochemical properties, particulate matter (PM) is one of the most important air pollutants that have adverse effects on human health. In particular, the composition of PM and its hazardous chemical content can adversely affect the health of an exposed individual [31]. More recent studies have confirmed the role of heavy metal toxicity in PM [32]. The deleterious effects of heavy metals on human health have been demonstrated in numerous ways. Exposure to these pollutants leads to acute and chronic toxicity and many diseases such as neurological disorders, dietary deficiency, hormonal imbalance, obesity, abortion, cardiopulmonary disease, liver and kidney damage, allergies and asthma, chronic viral infections, reduced body tolerance, infertility, anemia and fatigue, weakening of the immune system, genetic damage, premature aging, memory loss, osteoporosis, hair loss, insomnia and different types of cancer [33] and mental hypogenesis in children and death [34].

4. Conclusions

The study conducted aims to evaluate in the area of the Tongon gold mine, the level of contamination of suspended particles by heavy metals and their impact on the health of populations exposed to these pollutants.

The results indicate that the average concentrations of suspended particles ($PM_{2.5}$ and PM_{10}) obtained are all above the exposure limits recommended by Decree No. 2017-125 of February 22, 2017 on air quality, which are 25 and 50 μg/m^3 respectively for suspended particles $PM_{2.5}$ and PM_{10}. In addition, among the heavy metals contained in the suspended particles, the concentrations of the metals arsenic and nickel are high and all above the standard limit values which are 0.006 μg/m^3 and 0.02 μg/m^3 respectively for arsenic and nickel. The health risk assessment of water consumption and inhalation of PM_{10} suspended particles reveals that their consumption and inhalation over a long period of time could cause a low risk of carcinogenic effects. These results show the need for environmental monitoring, supporting the development of an effective remediation strategy to reduce local pollution and contamination.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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