The Review Of
DIABETIC
STUDIES OPEN ACCESS

Probabilistic Effects Of Mercury Exposure On The Health Of Gold Miners In Colombia

Irina Maudith Campos-Casarrubia[1] , María Osley Garzón-Duque[2] , Carlos Alberto Molina-Polo[3]

[1]Escuela de Enfermería – Universidad de Córdoba, Colombia
Email: *itamaudith@gmail.com* ORCID: *https://orcid.org/0000-0002-8736-9470*
[2]Facultad de Medicina – Universidad CES, Colombia Email: *mgarzon@ces.edu.co*
ORCID: *https://orcid.org/0000-0001-7261-3146*
[3]Escuela de Ciencias Ambientales – Universidad del Sinú, Colombia
Email: *camolinapolo@gmail.com* ORCID: *https://orcid.org/0000-0001-7732-460X*
Corresponding autor:
email: campos.irina@uces.edu.co

Abstract

Objective: To evaluate the influence of occupational and non-occupational exposure to mercury, occupational health and safety conditions on the clinical effects experienced by a group of artisanal and ancestral miners in Colombia.
Materials and methods: a cross-sectional quantitative study, primary sources of information, and an assisted survey of 103 gold miners. Exploratory, bivariate and multivariate analysis, Bayesian networks to probabilistically model three risk scenarios; current conditions, maximum and minimum possible degree of exposure.
Results: Most miners do not report obvious clinical symptoms, prolonged exposure and without adequate protection increases the risk of developing neurological and respiratory effects. The scenario of greater exposure, the incidence of tremors, paresthesia and respiratory problems increased dramatically.
Conclusion: The clinical effects evaluated showed a behavior, in which the risk is due to a deterministic influence and responds to individual and collective conditions, they can be linked to the social, economic, political, territorial, and public order levels, hence the exposure variables only explain a relative percentage of this public health problem. There is a need for a comprehensive approach that encompasses occupational and non-occupational protection, with a view to reducing the use and routes of exposure to mercury.

Keywords: public health; occupational health; mining; mercury; occupational exposure.

INTRODUCTION

Artisanal and small-scale gold mining (ASGM) represents a significant economic activity in certain regions worldwide, particularly in developing countries. This practice is closely linked to the use of elemental mercury, leading to severe environmental and public health issues, as evidenced by multiple studies [1,2,3].

Globally, approximately 37.0% of mercury released into environmental matrices originates from ASGM, primarily affecting rural communities in Africa, Asia, and Latin America, where livelihoods heavily depend on this economic activity. In these regions, mercury is used to amalgamate gold through chelation, facilitating its extraction and perpetuating the contamination cycle [4]. The Minamata Convention seeks to reduce global mercury use; however, its implementation has been complex and uneven, particularly in impoverished rural areas where technological alternatives and access to alternative economic development pathways remain scarce [5]. In this context, Latin America is among the most affected regions by mercury pollution from gold mining. In countries such as Peru, Bolivia, Ecuador, Brazil, and Colombia, mercury contaminates soils, water bodies, and

biota, impacting both human communities in mining-affected areas and broader ecosystemic cycles [6].

In Colombia, ASGM is particularly relevant in regions such as Bajo Cauca, Magdalena Medio, Chocó, La Mojana, and the San Jorge subregion, which includes the municipality of San José de Uré in the department of Córdoba, where the economy heavily depends on artisanal and ancestral gold extraction [7]. Consequently, assessing occupational and non-occupational exposure and the occupational safety conditions of miners in these communities is critical, as exposure is associated with a spectrum of health alterations. These range from short-term neurological symptoms such as tremors and sensory disorders to long-term conditions, including chronic respiratory diseases, cytogenetic damage, and central nervous system impairments [8].

Given these concerns, mercury exposure and its potential clinical effects in these communities are influenced by a multiplicity of factors and complex scenarios. Therefore, risk assessment should be approached using methodologies that comprehensively capture these realities, such as Bayesian networks, which enable modelling of multiple exposure spectra and scenarios while accurately accounting for exposure influences and uncertainty regarding health outcomes in miners and public health at large [9].

Based on these considerations, this study evaluated the short-, medium-, and long-term clinical effects of mercury exposure on the health of artisanal and ancestral gold miners in San José de Uré. Bayesian networks were used to model risk scenarios, estimating the role of occupational and non-occupational exposure, as well as occupational health and safety conditions, in the manifestation of clinically significant outcomes associated with mercury exposure, based on rigorous empirical and investigative evidence.

MATERIALS AND METHODS

A cross-sectional descriptive and quantitative study was conducted using primary data sources, derived from an assisted survey applied to a census of 103 gold miners. The study included male and female miners over 18 years old, residing and working in the study area for more than 10 years, who voluntarily agreed to participate and provided informed consent prior to data collection. These miners are part of ASOMATA (Association of Ancestral and Artisanal Miners) in the municipality of San José de Uré, in the department of Córdoba, Colombia. This study is a subproduct of the macroproject entitled: “Social and Environmental Vulnerability of a Population Residing in the Area of Influence of a Mining Zone in the San Jorge River Basin, Department of Córdoba, Colombia, under the Driving Forces Model, 2021-2025,” approved by Act No. 174, Project Code: 1027, from the Institutional Ethics Committee on Human Research of Universidad CES in 2021.

Prior to data collection, the main researcher and a fieldwork assistant, familiar with and actively engaged in community work with this mining population, underwent standardization training. A survey, validated by subject-matter experts, was administered between the second semester of 2023 and the first quarter of 2024. Instrument reliability was ensured through a pilot test, characterizing two key dimensions: exposure to elemental mercury and clinical effects of mercury exposure.

Selection bias was controlled by applying inclusion and exclusion criteria, while information bias was mitigated through the pilot test and standardization of data collectors. The survey instrument included variables previously used in similar populations, and workers underwent an awareness process explaining the study, its objectives, benefits, and data usage. Based on empirical, institutional [10], and scientific evidence [11,12,13], miners’ mercury exposure was stratified into two main types: occupational and non-occupational exposure, as well as exposure related to occupational health and safety conditions.

Exposure variables included elemental mercury exposure, use of elemental mercury and amalgam, duration of occupational exposure (years), use of protective equipment for hands, nose, mouth, and lower limbs, and frequency of food consumption at work. Reports of clinical damage (toxic effects derived from mercury exposure) were classified into short-, medium-, and long-term effects,

including dysgeusia or metallic taste sensation (short term), tremors during activities (short term), paresthesia or tingling/numbness (short term), decreased or impaired muscle strength in hands and feet (medium term), and respiratory diseases (asthma, pneumonia, etc.) (long term).

Exploratory analysis included absolute (n) and relative (rf) frequencies with 95.0% confidence intervals. All quantitative variables, except years of work experience, for which mean and standard deviation were reported, were recategorized for further analyses. Influence analysis using Bayesian networks probabilistically modelled three risk scenarios: current field-measured conditions, maximum possible exposure, and minimum possible exposure. This analysis estimated the joint influence of two occupational and non-occupational exposure variables—elemental mercury usage and gold extraction via amalgamation—on each clinical effect of mercury exposure.

Additionally, the independent influence of four key occupational health and safety variables (food consumption at work, use of dermal protection, use of respiratory protection, and use of lower limb protection) was simultaneously examined concerning selectively recorded health effects, based on relevant theoretical evidence [14,25]. The Bayesian network was constructed as a multifactorial detection model to estimate the probability of health effects associated with elemental mercury exposure, addressing three scenarios: 1. Probability of clinical effects occurring under field-recorded conditions; 2. Probability of clinical effects occurring under maximum possible elemental mercury exposure; and 3. Probability of clinical effects occurring under minimum possible elemental mercury exposure.

Descriptive analyses were conducted using Stata 18 MP (College Station, TX: StataCorp LLC), and the Bayesian network was modeled using Netica 7.0.1 (Norsys Software Corp) and its API for MATLAB in MATLAB R2024a (The MathWorks Inc, Natick, Massachusetts).

Bayesian network modelling and adjustment

The network was executed using the counting learning algorithm as an initial step, followed by an optimized compilation through stochastic search to maximize the likelihood of the conditional probability tables (CPTs) obtained from the interaction between instances or categories of each variable and to eliminate potential confounding effects. The degree of expertise for updating beliefs or knowledge about risk occurrence was set to 1, as an individually weighted learning analysis was performed based on the collected data, assuming a generalized Dirichlet distribution as a conjugate prior for multiple probabilities in the estimated risk occurrence. Consequently, the junction tree was constructed by minimizing network complexity through the reduction of clique sizes or subnetworks formed and their respective separator sets in 377 iterations. Likewise, the influence of exposure variables on estimated risks was quantified through a sensitivity analysis of clinical effects, calculating entropy reduction (ER) or mutual information and the percentage reduction of uncertainty induced by the three most relevant variables regarding the posterior distribution of the occurrence of each specific effect category.

RESULTS

The general characterization of the working conditions of ancestral and artisanal miners, considering their age ranges, shows that workers aged 45 to 59 years have dedicated the most relative time to artisanal mining, with work experience periods ranging from 21 to 30 years. Likewise, miners aged 30 to 44 years have also devoted a relatively long period to this activity. Regarding the use of elemental mercury, the 30 to 44-year-old group is the one that most frequently resorts to this heavy metal, while the 45 to 59-year-old group uses it to a lesser extent. Therefore, miners aged 30 to 44 stand out for having used this contaminant most regularly throughout their working careers. Additionally, this same group carries out the amalgamation process more frequently than the other age groups, while miners aged 60 or older report an almost non-existent use of this method for gold extraction (Table 1).

Table 1. Characterization of working conditions and Hg use among artisanal and ancestral miners

Variable	Age Range	N	Mode	Category	n	rf (%)	95% CI Lower	95% CI Upper
Work Time	18 to 29 years	16	6 to 10 years	1 to 5 years	2	12.5	0	28.7
				11 to 20 years	3	18.75	0	37.87
				21 to 30 years	0	0	0	0
				6 to 10 years	11	68.75	46.04	91.46
				More than 31 years	0	0	0	0
	30 to 44 years	43	11 to 20 years	1 to 5 years	6	13.95	3.6	24.31
				11 to 20 years	27	62.79	48.34	77.24
				21 to 30 years	7	16.28	5.24	27.31
				6 to 10 years	3	6.98	0	14.59
				More than 31 years	0	0	0	0
	45 to 59 years	33	21 to 30 years	1 to 5 years	0	0	0	0
				11 to 20 years	9	27.27	12.08	42.47
				21 to 30 years	16	48.48	31.43	65.54
				6 to 10 years	1	3.03	0	8.88
				More than 31 years	7	21.21	7.26	35.16
	60 years and older	11	More than 31 years	1 to 5 years	2	18.18	0	40.97
				11 to 20 years	3	27.27	0.95	53.59
				21 to 30 years	0	0	0	0
				6 to 10 years	0	0	0	0
				More than 31 years	6	54.55	25.12	83.97
Mercury Usage	18 to 29 years	16	No	No	11	68.75	46.04	91.46
				Yes	5	31.25	8.54	53.96
	30 to 44 years	43	No	No	25	58.14	43.39	72.88
				Yes	18	41.86	27.12	56.61
	45 to 59 years	33	No	No	30	90.91	81.1	100
				Yes	3	9.09	0	18.9
	60 years and older	11	Yes	No	5	45.45	16.03	74.88
				Yes	6	54.55	25.12	83.97

Mercury Use Duration	18 to 29 years	16	Years	Years	8	50	25.5	74.5
				Months	4	25	3.78	46.22
				No response	4	25	3.78	46.22
	30 to 44 years	43	Years	Years	24	55.81	40.97	70.66
				Months	10	23.26	10.63	35.88
				No response	9	20.93	8.77	33.09
	45 to 59 years	33	Years	Years	17	51.52	34.46	68.57
				Months	9	27.27	12.08	42.47
				No response	7	21.21	7.26	35.16
	60 years and older	11	No response	Years	2	18.18	0	40.97
				Months	4	36.36	7.94	64.79
				No response	5	45.45	16.03	74.88
Mercury Use Frequency	18 to 29 years	16	Occasionally	No response	7	43.75	19.44	68.06
				Occasionally	9	56.25	31.94	80.56
				Biweekly	0	0	0	0
				Weekly	0	0	0	0
	30 to 44 years	43	Occasionally	No response	11	25.58	12.54	38.62
				Occasionally	28	65.12	50.87	79.36
				Biweekly	2	4.65	0	10.95
				Weekly	2	4.65	0	10.95
	45 to 59 years	33	Occasionally	No response	14	42.42	25.56	59.29
				Occasionally	18	54.55	37.56	71.53
				Biweekly	0	0	0	0
				Weekly	1	3.03	0	8.88
	60 years and older	11	Occasionally	No response	2	18.18	0	40.97
				Occasionally	6	54.55	25.12	83.97
				Biweekly	0	0	0	0
				Weekly	3	27.27	0.95	53.59
Amalgam Burning	18 to 29 years	16	Yes	No	7	43.75	19.44	68.06
				Yes	9	56.25	31.94	80.56
	30 to 44 years	43	Yes	No	13	30.23	16.51	43.96
				Yes	30	69.77	56.04	83.49
	45 to 59 years	33	Yes	No	16	48.48	31.43	65.54
				Yes	17	51.52	34.46	68.57
	60 years and older	11	No	No	10	90.91	73.92	100
				Yes	1	9.09	0	26.08

Furthermore, (Table 2) shows that, in general terms, artisanal and ancestral miners tend to exhibit a relatively high level of exposure, which is mainly reflected in the relative frequencies of occupational and extra-occupational exposure to amalgam use and the average number of years of work experience (Figures 1-2-3). The use of elemental mercury during the extraction process suggests a potential trend toward reduced utilization. Overall, the relative frequencies of factors derived from exposure through occupational health and workplace safety reveal a similar mercury exposure pattern, characterized by a widespread lack of adoption and implementation of essential protective measures when handling this contaminant in gold extraction. However, lower limb protection differs from this trend, as miners tend to wear rubber boots and, to a lesser extent, shoes as protective elements.

Table 2. Characterization of occupational and non-occupational exposure, occupational health and safety, and clinical effects derived from mercury use in miners.

Dimension	Variable	Ncat	Mode	n	Category	n	rf (%)	95% CI Lower	95% CI Upper
Exposure	Frequency of food consumption at work	2	Always	62	Sometimes	41	39.81	30.35	49.26
					Always	62	60.19	50.74	69.65
	Use of amalgam	2	Yes	57	No	64	44.66	35.06	54.26
					Yes	75	55.34	45.74	64.94
	Use of elemental mercury	2	No	70	No	70	67.96	58.95	76.97
					Yes	33	32.04	23.03	41.05
	Use of dermal protection	2	None	95	Gloves	8	7.77	2.6	12.94
					None	89	92.23	87.06	97.4
	Use of respiratory protection	3	None	97	None	97	94.19	89.65	98.73
					Cloth mask	3	2.91	0.11	6.16
					Facemask	3	2.91	0.11	6.16
	Use of lower limb protection	5	Rubber boots	53	Rubber boots	53	51.46	41.81	61.11
					None	20	19.42	11.78	27.06
					Sandals	6	5.83	1.3	10.35
					Sneakers	5	4.85	0.7	9
					Shoes	19	18.45	10.96	25.94
Effect	Dysgeusia	3	Never	77	Never	77	74.76	66.37	83.15
					Once a day	5	4.85	0.7	9
					Once a month	21	20.39	12.61	28.17
	Tremors	3	Never	82	Never	82	79.61	71.83	87.39

					Once a day	15	14.56	7.75	21.38
					Once a month	6	5.83	1.3	10.35
				67		66	65.05	55.84	74.26
	Paresthesia	4	Never	7	Never	7	5	4	6
					Once a day	5	4.85	0.7	9
					Once a month	26	25.24	16.85	33.63
					Once a week	5	4.85	0.7	9
				75		77	72.82	64.22	81.41
	Limb strength loss	4	Never	5	Never	5	2	2	1
					Once a day	3	2.91	0.11	6.16
					Once a month	19	18.45	10.96	25.94
					Once a week	6	5.83	1.3	10.35
				82		88	79.61	71.83	87.39
	Respiratory problems	2	No	2	No	22	1	3	9
					Yes	21	20.39	12.61	28.17

n: absolute frequency
rf: relative frequency

Regarding the clinical effects studied, the trend is nearly uniform, with the majority (rf) of artisanal and ancestral miners reporting no symptoms associated with the five clinical effects derived from occupational and workplace exposure to elemental mercury. However, there were some reports of symptoms occurring at least once a day or once a month, particularly for dysgeusia and symptoms related to neuromotor disorders, respectively. Among these effects, paresthesia had the highest reported occurrence among miners. Thus, the general pattern of symptom occurrence for the five clinical effects followed this order: Never (No) > At least once a month > At least once a day > At least once a week.

The risk probability estimation, based on instrument records, indicates that the observed conditions of occupational and non-occupational exposure, as well as occupational health and safety among artisanal and ancestral miners, result in conditional probabilities that describe a generalized tendency toward the non-occurrence of the characterized clinical effects. However, it is important to note that some probabilities, while relatively small, were still significant in the development of at least one manifestation of the analysed effects. In this regard, occupational and non-occupational exposure variables suggest a relatively higher probability of risk in the occurrence of the characterized clinical effects (Figure 1).

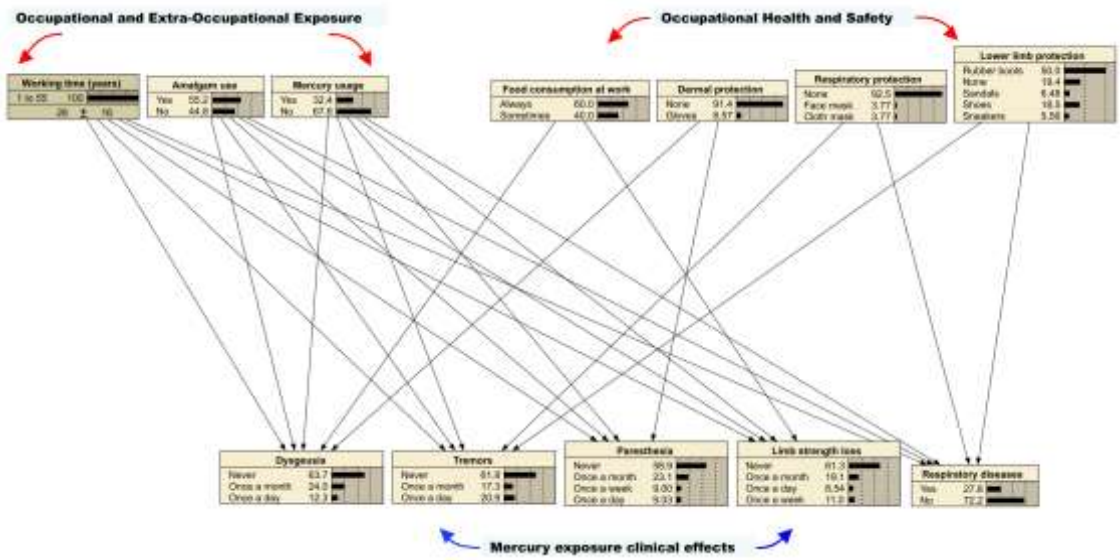

Figure 1. Probabilities for clinical effect occurrence based on conditions recorded during field measurements.

Nonetheless, in the scenario where miners experience the highest possible degree of exposure to elemental mercury, the conditional probabilities of developing clinical effects change drastically. The majority of these probabilities indicate a strong likelihood of severe health effects, including an increase in the occurrence of tremors (at least once a day), paresthesia (at least once a month), muscle strength deterioration (at least once a month), and the prevalence of respiratory problems. In contrast, dysgeusia shows a higher individual probability of non-occurrence, although its joint probability of occurrence at least once a month or at least once a day reaches 47.1% (Figure 2).

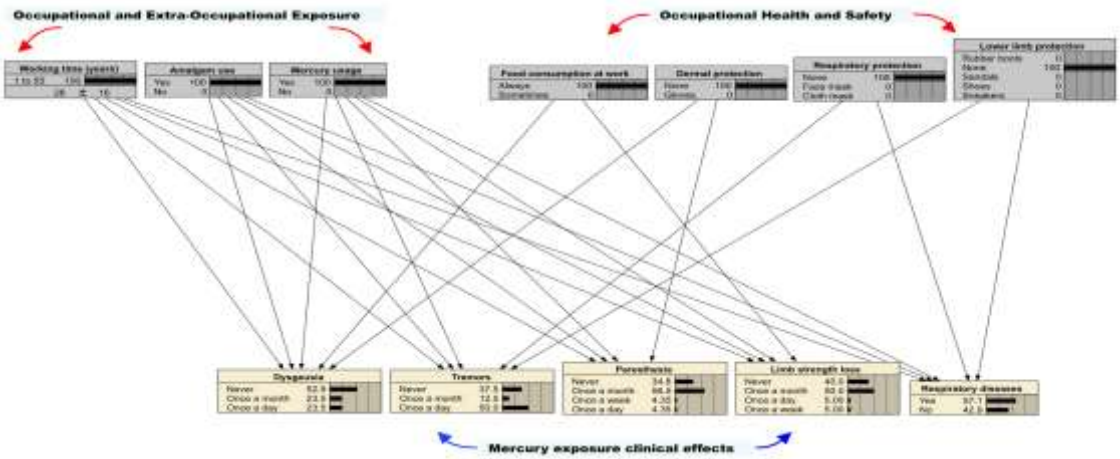

Figure 2. Probabilities for clinical effect occurrence under the highest possible exposure to elemental mercury.

Conversely, in the scenario where miners experience the lowest possible degree of exposure to elemental mercury, there was a drastic and uniform reduction in the probability of experiencing all clinical effects and their respective manifestations. This suggests that, despite the absence of other potential exposure factors in the model, reducing exposure through the evaluated factors has a critical impact on the conditional probabilities of health alterations. This highlights the importance of using and implementing safety measures and protocols when utilizing elemental mercury in gold extraction (Figure 3).

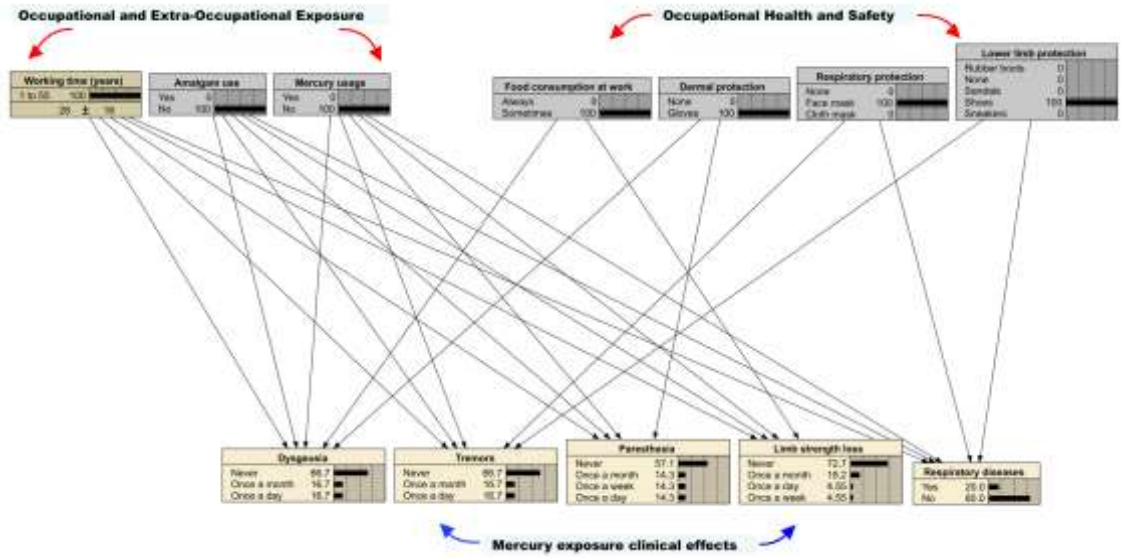

Figure 3. Probabilities for clinical effect occurrence under the lowest possible exposure to elemental mercury.

The combination of conditional probabilities that leads to the greatest risk reduction involves a total cessation of elemental mercury and amalgam use, along with decreased frequency of food consumption at work and the use of gloves, face masks, and shoes.

Regarding the influence of exposure type on the short-term toxicological effects of mercury, Table 3 shows that the clinical manifestations of dysgeusia, tremors, and paresthesia share a common and primary influence from the use of elemental mercury and amalgam. Food consumption at work and hand protection are closely related to the occurrence of paresthesia and dysgeusia, while respiratory protection is associated with tremors. In line with this, the medium-term effects evaluation reveals that muscle strength deterioration in miners' extremities is strongly linked to the use of elemental mercury in gold extraction activities and, to a lesser extent, to food consumption at work and amalgam use.

Table 3. Influence of elemental mercury exposure factors on conditional probabilities for occurrence of typified clinical effects.

Effect/Risk Factor	Entropy Reduction	Percentage (%)
Dysgeusia	1.28	100
Food consumption at work	0.235	18.363
Use of elemental mercury	0.227	17.715
Hand protection	0.204	15.895
Tremors	1.34	100
Use of elemental mercury	0.233	17.366
Respiratory protection	0.195	14.556
Use of amalgam	0.129	9.622
Paresthesia	1.564	100
Use of amalgam	0.629	40.227
Use of elemental mercury	0.477	30.516
Hand protection	0.196	12.557
Muscle strength deterioration	1.544	100
Use of elemental mercury	0.458	29.665
Food consumption at work	0.136	8.791
Use of amalgam	0.113	7.295
Respiratory diseases	0.853	100
Lower limbs protection	0.286	33.498

Respiratory protection	0.126	14.82
Use of elemental mercury	0.123	14.363

Meanwhile, the occurrence of chronic respiratory diseases such as asthma and pneumonia were significantly influenced by lower limb protection, followed by the influence of respiratory protection and elemental mercury use, suggesting that occupational health and safety measures have a greater impact.

In general, the reduction in uncertainty regarding the influence of exposure factors on the studied clinical effects follows a pattern: paresthesia (83.3%) > respiratory diseases (62.7%) > dysgeusia (52.1%) > muscle strength deterioration (45.8%) > tremors (41.5%).

The complexity of network's estimates indicates that 5 cliques or fully connected subnetworks were formed, through which the influences of exposure factor conditional probabilities on health effects were estimated. The size (importance) and members of each clique align with the entropy reduction (uncertainty) estimated in Table 2. In this regard, it is noteworthy that each clinical effect describes a higher degree of relative connection with the 3 most relevant exposure factors. This is reflected in the size of cliques 1 and 2, as well as cliques 3, 4, and 5, which, though smaller in size, still maintain important relationships; reflecting high interdependence (especially clique 3) and diversity in the influences of risk conditional probabilities quantified by the network. Consequently, the evaluated network was characterized as complex and sensitive to the multifactorial influence of both occupational and extra-occupational exposure, as well as the occupational health and safety of artisanal and ancestral miners (Table 4).

Table 4. Structure and complexity of the junction tree for risk conditional probabilities estimated by the network (in green, the most influential exposure factors and in bold, their associated clinical effects).

Clique	Links	Size	Memberships
1	2	180	PROTResp, TiempLAB, UtilAMALG, HgAzogH, PROTMif, ***Tremors**
2	1, 3	120	***RespProb**, PROTResp, TiempLAB, UtilAMALG, HgAzogH, PROTMif
3	2, 4, 5	48	FoodWork, PROTDerm, ***MetalTaste**, TiempLAB, UtilAMALG, HgAzogH
4	3	32	***ExposureBMP**, PROTDerm, TiempLAB, UtilAMALG, HgAzogH
5	3	32	***MuscleDecline**, FoodWork, TiempLAB, UtilAMALG, HgAzogH
Total		412	(With separation sets = 492)

DISCUSSION

The occupational exposure conditions to elemental mercury observed in artisanal and ancestral miners of San José de Uré constitute a concerning issue for the public health stability of this community, as the characterization of the miners reflects a significant exposure rate, which aligns with the results of various studies addressing health risks associated with small-scale gold mining in regions of Asia, Africa, and Latin America. In these areas, workers are exposed through a series of chronic exposure routes, primarily via inhalation of mercury vapors during the handling and storage of this contaminant, and finally during gold amalgamation and subsequent burning of the amalgam [25,26].

In this way, chronic exposure triggers pathological processes primarily related to the neurotoxic effects of mercury, such as paresthesia, dysgeusia, and tremors, among other progressive neurological disorders, as the main biological mechanism explaining mercury toxicity in these

scenarios is its ability to cross the blood-brain barrier, directly affecting the central nervous system as an acute toxic effect in the short term[27]. Furthermore, previous studies have documented how the systematic accumulation of mercury in the central nervous system is linked to motor and sensory alterations in coordination and movement of the limbs, such as those that have the potential to prevail in the mining population under maximum exposure to elemental mercury evaluated [28]. Additionally, elemental or inorganic mercury used by miners tends to rapidly transform into methylmercury in aquatic ecosystems, such as those where ancestral and artisanal mining takes place, increasing absorption rates and the risk of individual and community toxicity, compounded by gastrointestinal absorption when contaminated food is ingested, particularly in the work environment [29].

These dynamics highlight the importance of the miners' extra-occupational exposure conditions, as multiple pieces of evidence show that work time, storage, and exposure to volatilized mercury, which is often stored, represent a main exposure vector for miners and their families. In areas where small-scale gold mining is practiced, exposure to this contaminant is not limited to primary emission sources, but extends in a multidimensional manner, creating a public health issue that transcends occupational health and safety conditions [30]. In this sense, this could provide a possible explanation for the low probabilistic occurrence of clinical effects observed in the miners of San José de Uré, as the conditional probabilities of the occurrence of evident alterations tend to be largely influenced by the three extra-occupational exposure factors evaluated [31].

The poor use of protective and safety measures among miners may be due to a lack of access to essential information concerning the prevention of alterations and deleterious effects caused by systemic mercury exposure, but primarily to a lack of interest in implementing such preventive measures. This not only responds to particular economic limitations but also to deeply entrenched socio-cultural factors in mining communities such as San José de Uré [32]. Thus, in many cases, miners perceive the use of protective equipment, such as gloves, boots, goggles, or masks, as an obstacle to productivity rather than an essential tool for preserving their health, prioritizing immediate income generation over medium- and long-term occupational safety, as they opt to maximize productivity. This implies a complex web of factors and conditions that shape the ways in which artisanal and ancestral miners are exposed and how the potential implications and effects of mercury contamination manifest at various scales [33].

This normalization of risk can be understood as a psycho-laboral process that reinforces the acceptance of dangerous working conditions as an inherent part of daily life in gold mining. Although miners may be aware of certain risks, they tend to minimize potential dangers by not witnessing immediate and significant health effects, reinforcing the idea that risks are manageable or even irrelevant, leading to an underestimation of long-term public health effects [34].

However, it is imperative to plan, manage, and implement territorial strategies and policies aimed at the gradual and adaptive adoption of occupational health and safety measures for miners. These should not only focus on providing protective equipment but also modify miners' perceptions and cultural paradigms regarding mercury use, directly and actively involving the community in risk management through participatory approaches.

Consequently, the characterization and probabilistic evaluation reflected the complexity of these processes, outlining specificity in the occurrence of short-, medium-, and long-term effects, particularly responding to the use of protective and safety measures such as hand protection, respiratory protection, and protection for lower limbs. In the scenario of minimal possible exposure, these represent primary barriers that, when systematically and appropriately adopted, have the potential to substantially reduce the intensity and frequency of exposure, thereby decreasing the probability of clinical effects addressed [35].

In general, the conditional occurrence of the evaluated clinical effects showed complex behavior, where the risk is not only determined by a deterministic influence but also responds to the spectrum of individual and collective conditions of the miners. These are not limited exclusively to their work activities, as they are also linked to the uncertainty posed by social, economic, political, territorial,

and public order changes and variations in San José de Uré. Hence, the exposure variables evaluated only explained a relative percentage of this public health issue [36].

Therefore, these findings represent an approximation to the real prevalence of risk, where, depending on the factors and spectra considered, as well as their possible scenarios, clinical and toxicological manifestations associated with mercury use in small-scale gold mining will tend to vary. Risk is understood as a multifactorial response that must be triangulated based on the specificity of each context and the comprehensive reduction of exposure means, frequency, and pathways to mercury and its derivatives [37].

CONCLUSIONS

Working conditions of the surveyed ancestral and artisanal gold miners reveal significant exposure in their daily work. The vast majority have been in this activity for more than 20 years, and those miners aged 30 to 44 are the ones who most frequently resort to the use of elemental mercury, having a higher risk of exposure as they also come into contact with the amalgamation process.

Studied clinical effects revealed complex behavior, where risk is not only due to a deterministic influence but also responds to the spectrum of individual and collective conditions of the miners, which may be linked to social, economic, political, territorial, and public order conditions. Therefore, the evaluated exposure variables only explained a relative percentage of this public health issue.

The findings of this study serve as rigorous evidence regarding the evaluation of the risk of mercury exposure in artisanal and ancestral gold mining communities, using a probabilistic and inferential approach through Bayesian networks, which proves to be a useful tool for differential and prospective risk analysis and the influence of the considered exposure factors. Additionally, the results emphasize the importance of interventions aimed at modifying perceptions of the risks associated with mining activities, highlighting the need for a comprehensive approach that encompasses both occupational and extra-occupational protection, as well as occupational safety and health measures, with the goal of reducing the use and exposure pathways to elemental mercury in small-scale gold mining communities like San José de Uré.

ACKNOWLEDGEMENTS

The authors would like to thank all the authorities and staff from the three universities that participated,who contributed this study to take place.

AUTHOR CONTRIBUTIONS

Research concept: Irina Campos María Garzón Carlos Molina
Research methodology: Irina Campos María Garzón Carlos Molina
Collecting material: Irina Campos María Garzón
Statistical analysis: Irina Campos María Garzón
Anuchart KaunnilInterpretation of results: Carlos Molina
References: Carlos Molina

Highlights

- Most miners don't show obvious symptoms despite prolonged mercury exposure.
- Increased exposure drastically raises risk of tremors, paresthesia, and respiratory problems.
- Clinical effects are influenced by individual and collective conditions, not just exposure.
- There's a need for comprehensive protection (occupational and non-occupational) to reduce mercury exposure.
- Bayesian networks are a useful tool for probabilistic risk analysis of mercury exposure.

REFERENCES

1. Tsang VWL, Lockhart K, Spiegel SJ, Yassi A. Occupational Health Programs for Artisanal and Small-Scale Gold Mining: A Systematic Review for the WHO Global Plan of Action for Workers'

Health [Internet]. Vol. 85, Annals of Global Health. Ubiquity Press, Ltd.; 2019. p. 128. Available from: http://dx.doi.org/10.5334/aogh.2592
2. Donkor P, Siabi EK, Frimpong K, Mensah SK, Siabi ES, Vuu C. Socio-demographic effects on role assignment and associated occupational health and safety issues in artisanal and small-scale gold mining in Amansie Central District, Ghana [Internet]. Vol. 9, Heliyon. Elsevier BV; 2023. p. e13741. Available from: http://dx.doi.org/10.1016/j.heliyon.2023.e13741
3. Ondayo MA, Watts MJ, Humphrey OS, Osano O. Public health assessment of Kenyan ASGM communities using multi-element biomonitoring, dietary and environmental evaluation [Internet]. Vol. 277, Ecotoxicology and Environmental Safety. Elsevier BV; 2024. p. 116323. Available from: http://dx.doi.org/10.1016/j.ecoenv.2024.116323
4. Esdaile LJ, Chalker JM. The mercury problem in artisanal and small-scale gold mining. Chemistry [Internet]. 2018;24(27):6905–16. Available from: http://dx.doi.org/10.1002/chem.201704840
5. Spiegel S, Keane S, Metcalf S, Veiga M. Implications of the Minamata Convention on Mercury for informal gold mining in Sub-Saharan Africa: from global policy debates to grassroots implementation? [Internet]. Vol. 17, Environment, Development and Sustainability. Springer Science and Business Media LLC; 2014. p. 765–85. Available from: http://dx.doi.org/10.1007/s10668-014-9574-1
6. Cheng Y, Nakajima K, Nansai K, Seccatore J, Veiga MM, Takaoka M. Examining the inconsistency of mercury flow in post-Minamata Convention global trade concerning artisanal and small-scale gold mining activity. Resour Conserv Recycl [Internet]. 2022;185(106461):106461. Available from: http://dx.doi.org/10.1016/j.resconrec.2022.106461
7. Bustamante N, University of Queensland, Danoucaras N, McIntyre N, Díaz-Martínez JC, Restrepo-Baena OJ, et al. Review of improving the water management for the informal gold mining in Colombia. Rev Fac Ing Univ Antioq [Internet]. 2016;(79). Available from: http://dx.doi.org/10.17533/udea.redin.n79a16
8. Crespo-Lopez ME, Augusto-Oliveira M, Lopes-Araújo A, Santos-Sacramento L, Souza-Monteiro JR, da Rocha FF, et al. Mercury neurotoxicity in gold miners. In: Advances in Neurotoxicology. Elsevier; 2022. p. 283–314. https://doi.org/10.1016/bs.ant.2022.04.003
9. Kaikkonen L, Parviainen T, Rahikainen M, Uusitalo L, Lehikoinen A. Bayesian networks in environmental risk assessment: A review. Integr Environ Assess Manag [Internet]. 2021;17(1):62–78. Available from: http://dx.doi.org/10.1002/ieam.4332
10. Rivas-Casarrubia J.D. Evaluación del Manejo de Suelos Contaminados por actividad minera en el sur del departamento de Córdoba y el Bajo Cauca Antioqueño. Universidad Santo Tomás Tunja; 2021. https://repository.usta.edu.co/handle/11634/36730
11. Cárdenas, J., Arcos, A., & Echavarría, E. Seguridad y salud en la pequeña minería colombiana: estudios de caso en oro y carbón. Mape Responsable, 2021;10, 7-121. https://www.responsiblemines.org/wp-content/uploads/2017/07/07-10-2017-Somos-Tesoro-Seguridad-y-Salud.compressed.pdf
12. Mensah SK, Siabi EK, Donkor P, Kurantin N. Assessing the safety and health practices in the artisanal and small-scale gold mining sector of Ghana: A case of Ntotroso. Environmental Challenges. 2022;6(100443):100443. http://dx.doi.org/10.1016/j.envc.2022.100443
13. Arthur-Holmes F, Abrefa Busia K. Safety concerns and occupational health hazards of women in artisanal and small-scale mining in Ghana. Extr Ind Soc. 2022;10(101079):101079. http://dx.doi.org/10.1016/j.exis.2022.101079
14. Kwesi SS, Dartey E, Kuffour RA, Dekugmen DY, Osei-Bonsu R, Mintah DK, et al. Occupational health and safety practices among small-scale mining workers in Ghana. European Journal of Science, Innovation and Technology. 2024 [citado el 8 de octubre de 2024];4(2):26–39. https://www.ejsit-journal.com/index.php/ejsit/article/view/396
15. Bose-O'Reilly S, Bernaudat L, Siebert U, Roider G, Nowak D, Drasch G. Signs and symptoms of mercury-exposed gold miners. Int J Occup Med Environ Health [Internet]. 2017;30(2):249–69. Disponible en: http://dx.doi.org/10.13075/ijomeh.1896.00715
16. Taux K, Kraus T, Kaifie A. Mercury exposure and its health effects in workers in the artisanal and small-scale gold mining (ASGM) sector-A systematic review. Int J Environ Res Public Health [Internet]. 2022;19(4):2081. Disponible en: http://dx.doi.org/10.3390/ijerph19042081

17. Gibb H, O'Leary KG. Mercury exposure and health impacts among individuals in the artisanal and small-scale gold mining community: a comprehensive review. Environ Health Perspect [Internet]. 2014;122(7):667–72. Disponible en: http://dx.doi.org/10.1289/ehp.1307864
18. Afrifa J, Opoku YK, Gyamerah EO, Ashiagbor G, Sorkpor RD. The clinical importance of the mercury problem in artisanal small-scale gold mining. Front Public Health [Internet]. 2019;7:131. Available from: http://dx.doi.org/10.3389/fpubh.2019.00131
19. Ghasemi F, Aghaei H, Askaripoor T, Ghamari F. Analysis of occupational accidents among nurses working in hospitals based on safety climate and safety performance: a Bayesian network analysis. Int J Occup Saf Ergon [Internet]. 2022;28(1):440–6. Available from: http://dx.doi.org/10.1080/10803548.2020.1768759
20. Zhao L, Yin J, Huan J, Han X, Zhao D, Song J, et al. A Bayesian network for estimating hypertension risk due to occupational aluminum exposure. Chronic Dis Transl Med [Internet]. 2024;10(2):130–9. Available from: http://dx.doi.org/10.1002/cdt3.134
21. Nopriadi, Z.S, Ridwan A, & Dedi A. The Influence of Illegal Gold Mining Activities toward Health of Workers in Kuantan Singingi, Indonesia. International Journal of Science and Research (IJSR) ISSN (Online) 2015;2319-7064. https://www.ijsr.net/articlerating.php?paperid=SUB157856
22. Tomicic C, Vernez D, Belem T, Berode M. Human mercury exposure associated with small-scale gold mining in Burkina Faso. Int Arch Occup Environ Health [Internet]. 2011;84(5):539–46. Available from: http://dx.doi.org/10.1007/s00420-011-0615-x
23. Schutzmeier P, Berger U, Bose-O'Reilly S. Gold mining in Ecuador: A cross-sectional assessment of mercury in urine and medical symptoms in miners from Portovelo/Zaruma. Int J Environ Res Public Health [Internet]. 2016;14(1). Available from: http://dx.doi.org/10.3390/ijerph14010034
24. Steckling N, Tobollik M, Plass D, Hornberg C, Ericson B, Fuller R, et al. Global burden of disease of mercury used in artisanal small-scale gold mining. Ann Glob Health [Internet]. 2017;83(2):234–47. Available from: http://dx.doi.org/10.1016/j.aogh.2016.12.005
25. Saalidong BM, Aram SA. Mercury exposure in artisanal mining: Assessing the effect of occupational activities on blood mercury levels among artisanal and small-scale goldminers in Ghana. Biol Trace Elem Res [Internet]. 2022;200(10):4256–66. Available from: http://dx.doi.org/10.1007/s12011-021-03025-1
26. Vergara-Murillo F, González-Ospino S, Cepeda-Ortega N, Pomares-Herrera F, Johnson-Restrepo B. Adverse health effects and mercury exposure in a Colombian artisanal and small-scale gold mining community. Toxics [Internet]. 2022;10(12):723. Available from: http://dx.doi.org/10.3390/toxics10120723
27. Santa-Rios A, Barst BD, Tejeda-Benitez L, Palacios-Torres Y, Baumgartner J, Basu N. Dried blood spots to characterize mercury speciation and exposure in a Colombian artisanal and small-scale gold mining community. Chemosphere [Internet]. 2021;266(129001):129001. Available from: http://dx.doi.org/10.1016/j.chemosphere.2020.129001
28. Basu N, Bastiansz A, Dórea JG, Fujimura M, Horvat M, Shroff E, et al. Our evolved understanding of the human health risks of mercury. Ambio [Internet]. 2023;52(5):877–96. Available from: http://dx.doi.org/10.1007/s13280-023-01831-6
29. Morgan VL, Casso-Hartmann L, Velez-Torres I, Vanegas DC, Muñoz-Carpena R, McLamore ES, et al. Modeling exposure risk and prevention of mercury in drinking water for artisanal-small scale gold mining communities. Hum Ecol Risk Assess [Internet]. 2021;27(6):1492–508. Available from: http://dx.doi.org/10.1080/10807039.2020.1855576
30. Mambrey V, Rakete S, Tobollik M, Shoko D, Moyo D, Schutzmeier P, et al. Artisanal and small-scale gold mining: A cross-sectional assessment of occupational mercury exposure and exposure risk factors in Kadoma and Shurugwi, Zimbabwe. Environ Res [Internet]. 2020;184(109379):109379. Available from: http://dx.doi.org/10.1016/j.envres.2020.109379
31. Smith NM, Ali S, Bofinger C, Collins N. Human health and safety in artisanal and small-scale mining: an integrated approach to risk mitigation. J Clean Prod [Internet]. 2016;129:43–52. Available from: http://dx.doi.org/10.1016/j.jclepro.2016.04.124
32. Ajith MM, Ghosh AK, Jansz J. A mixed-method investigations of work, government and social factors associated with severe injuries in artisanal and small-scale mining (ASM) operations.

Saf Sci [Internet]. 2021;138(105244):105244. Available from: http://dx.doi.org/10.1016/j.ssci.2021.105244
33. Smith NM. "Our gold is dirty, but we want to improve": Challenges to addressing mercury use in artisanal and small-scale gold mining in Peru. J Clean Prod [Internet]. 2019;222:646–54. Available from: http://dx.doi.org/10.1016/j.jclepro.2019.03.076
34. Quispe Aquin R, Malone A, Smith NM, García Zúñiga FF. Perceptions and realities of mercury contamination in a Peruvian artisanal and small-scale gold mining (ASGM) community. Environ Res [Internet]. 2022;214(Pt 2):114092. Available from: http://dx.doi.org/10.1016/j.envres.2022.114092
35. Adler Miserendino R, Bergquist BA, Adler SE, Guimarães JRD, Lees PSJ, Niquen W, et al. Challenges to measuring, monitoring, and addressing the cumulative impacts of artisanal and small-scale gold mining in Ecuador. Resour Policy [Internet]. 2013;38(4):713–22. Available from: http://dx.doi.org/10.1016/j.resourpol.2013.03.007
36. Armah FA, Boamah SA, Quansah R, Obiri S, Luginaah I. Unsafe occupational health behaviors: Understanding mercury-related environmental health risks to artisanal gold miners in Ghana. Front Environ Sci [Internet]. 2016;4. Available from: http://dx.doi.org/10.3389/fenvs.2016.00029
37. Zolnikov TR, Ramirez Ortiz D. A systematic review on the management and treatment of mercury in artisanal gold mining. Sci Total Environ [Internet]. 2018;633:816–24. Available from: http://dx.doi.org/10.1016/j.scitotenv.2018.03.241