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Assessment of radiological exposure levels in the artisanal mining sector and victim management: a case study of Lualaba province, Democratic Republic of Congo

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ABSTRACT

Background. Artisanal mining in the Democratic Republic of Congo exposes workers to largely unrecognized radiological risks.

Objective. To assess ionizing radiation exposure levels, miners' knowledge and practices, and the health system's capacity to manage victims in Lualaba Province.

Methods. A cross-sectional descriptive and analytical study was conducted from December 2025 to March 2026. A total of 110 artisanal miners from three sites — Kolwezi ($n = 34$), Lubudi ($n = 32$), and Mutshatsha ($n = 44$) — and 10 health professionals were included. Dosimetric measurements used a Saphydose-N survey meter ($\mu\text{Sv/h}$) and an Inspector Alert scintillometer (Bq/cm^2). Standardized questionnaires assessed knowledge, attitudes, and practices (KAP). Statistical analyses used χ^2 or Fisher's exact test, ANOVA or Kruskal-Wallis test, and multivariable binary logistic regressions. Significance was set at $p < .05$.

Results. Mean ambient dose was $2.45 \pm 1.23 \mu\text{Sv/h}$ (maximum: $8.90 \mu\text{Sv/h}$ in Lubudi), approximately 10 times the local background ($0.24 \mu\text{Sv/h}$). Mean surface contamination on hands was $0.85 \pm 0.55 \text{ Bq/cm}^2$ (maximum: 2.40 Bq/cm^2). No miner wore radiation-specific personal protective equipment (PPE). Ignorance of radiation existence concerned 71.8% of miners (79/110), with a significant difference between sites, $\chi^2(2, N = 110) = 10.30, p = .006$. Respiratory symptoms were most frequent (42.7%). In multivariable analysis, working in Lubudi ($\text{OR} = 4.97$; 95% CI [1.82, 13.56]; $p = .002$) and extracting uranium ($\text{OR} = 6.34$; 95% CI [2.01, 20.00]; $p = .001$) were independent risk factors for high exposure ($> 3 \mu\text{Sv/h}$). Low education level was the only factor associated with risk unawareness ($\text{OR} = 3.45$; 95% CI [1.45, 8.21]; $p = .005$). Among health workers, 80% were unaware of the 20 mSv/year regulatory limit, no radiological accident management protocol existed, and the mean hospital preparedness score was 2/20 (10%).

Conclusion. Artisanal miners in Lualaba are exposed to dangerously high radiation levels, in a context of massive risk unawareness and a totally inadequate health system. An integrated model of prevention, dosimetric surveillance, and emergency medical training is proposed.

Keywords: natural radiation; uranium; artisanal miners; dosimetry; health system; Lualaba; Democratic Republic of Congo; logistic regression.

1. Introduction

The Democratic Republic of Congo (DRC) possesses exceptional mineral resources, concentrating more than 50% of global cobalt reserves and significant deposits of copper, uranium, and coltan (Banza Lubaba Nkulu et al., 2018; Bouramdane, 2023). Lualaba Province, with its mining towns and territories of Kolwezi, Lubudi, and Mutshatsha, is the epicenter of this geological wealth. According to Batumike et al. (2007), Lualaba holds approximately 10% of global copper reserves and 3.4 million tons of cobalt.

Alongside industrial mining, artisanal and small-scale mining (ASM) has grown exponentially in recent decades, involving nearly two million people in the DRC (Konkobo & Sawadogo, 2020). This activity, while economically lucrative for local communities, takes place under deplorable working conditions: lack of protective equipment, unconsolidated pits, direct handling of minerals without any risk training (Verbruggen, 2021; Pyana Kitenge et al., 2022).

Among the unrecognized occupational risks is natural radioactivity. Minerals associated with copper and cobalt, notably uraninite (UO_2) and torbernite ($\text{Cu}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$), contain radionuclides from the uranium-238 and thorium-232 decay chains (Loska & Wiechula, 2017; Bouramdane, 2023). Chronic exposure to ionizing radiation (gamma, alpha via dust inhalation, and skin contamination) is recognized as a definite carcinogen (Group 1) by the International Agency for Research on Cancer (IARC, 2012).

The health effects of chronic low-dose radiation exposure are well documented: leukemias, lung cancers, pulmonary fibrosis, kidney damage, and cataracts (NRC, 2006; UNSCEAR, 2020). The International Commission on Radiological Protection (ICRP, 2007) sets the annual effective dose limit for exposed workers at 20 mSv/year. However, in low- and middle-income countries, the application of these standards is virtually non-existent in the informal sector (Leuraud et al., 2015).

In the DRC, the health system, already weakened by decades of political crises and chronic underinvestment, has no diagnostic or therapeutic capacity to manage acute radiation syndrome or internal contamination (Nemery & Banza Nkulu Lubaba, 2020). The absence of dosimeters, alpha/beta counters, decontamination protocols, and decorporation treatments (DTPA, EDTA) is total (Kitobo, 2020). A recent study by Pyana Kitenge et al. (2022) reported a high prevalence of respiratory diseases among artisanal miners in Katanga, but without investigating the radiological component. Furthermore, the 2018 Congolese Mining Code,

while innovative in fiscal and environmental terms, does not provide any specific provisions for radiological protection of artisanal miners (Lassourd, 2018; Kitobo, 2020).

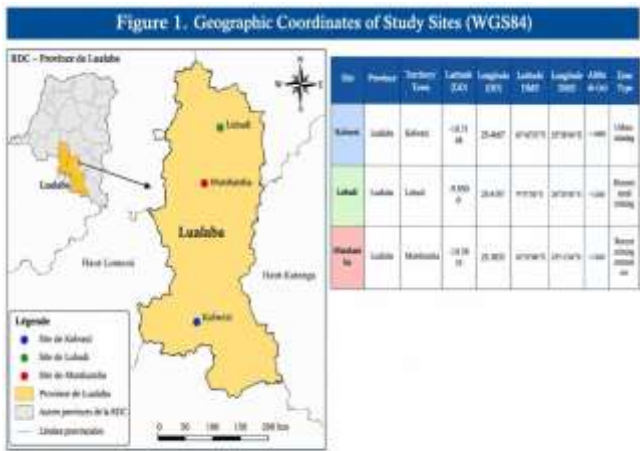
Artisanal mining sites in Lualaba Province, particularly in Kolwezi, Lubudi, and Mutshatsha, are mineral extraction zones where most work is done manually by digging shallow pits or galleries, using simple tools: hammers, shovels, picks. Mineral processing takes place in rivers or basins. Although neglected globally, this sector is inseparable from the national and provincial economy, as it reduces unemployment by offering a large job market to the local population; it accounts for 10–20% of global cobalt production.

In this sector, activities are sometimes informal or poorly regulated; operators may be independent or in cooperative structures. Although it contributes to the economy, it demands strength and high physical performance. The mining sector presents many challenges: environmental challenges (water pollution, destruction or disturbance of fauna and flora, soil degradation, erosion and landslides) and health challenges (regular intoxication and permanent contamination), as well as child labor on mining sites, which explains the low schooling of youth in the mining province of Lualaba.

2. Materials and methods

2.1. Study Design, Period, and Setting

This was a cross-sectional descriptive and analytical study conducted from December 2025 to March 2026. The study took place in three areas of Lualaba Province: Kolwezi (urban-mining area, provincial capital), Lubudi (historic rural mining area, known for its uranium deposits), and Mutshatsha (recent mining extension area). Lualaba Province covers 121,309 km² and has approximately 3.4 million inhabitants (World Bank, 2021).



Note. DD = decimal degrees; DMS = degrees, minutes, seconds. Coordinates are approximate for the administrative centers; exact mining sites may be located a few kilometers away. GPS coordinates of each specific mining site should be recorded for precise mapping.

2.2. Population and Sampling

Due to constraints related to the study and the large number of miners concerned, the study included 110 active miners at the sites. These participants were selected from those available at the time of the study and who freely agreed to take part, distributed as follows: Kolwezi (n = 34; 30.9%), Lubudi (n = 32; 29.1%), Mutshatsha (n = 44; 40.0%). Inclusion criteria were: being at least 15 years old, working at the site for at least 3 months, and consenting to participate.

Ten health professionals working in primary care structures (health centers, company clinics) and at Mwangeji General Reference Hospital (Kolwezi) were included exhaustively.

2.3. Variables and Measurement Instruments

2.3.1. Radiological Measurements

Ambient dose (gamma dose rate). Measured using a Saphydose-N survey meter equipped with a NaI(Tl) scintillator, expressed in microsieverts per hour (µSv/h). Measurements were taken at 1 m from the ground (whole-body exposure) and at 10 cm from the mineral (direct contact). Natural background was measured more than 500 meters from mining sites. Each site underwent 10 repeated measurements.

Surface contamination (beta-gamma). Measured using a portable Inspector Alert scintillometer (S.E. International, Inc.), expressed in becquerels per square centimeter (Bq/cm²).

Measurements were taken on the hands, clothing (chest and forearms), and tools of 20 miners randomly selected per site.

Annual effective dose. Estimated using the formula: Annual dose (mSv/year) = Mean hourly dose ($\mu\text{Sv/h}$) $\times$ 8 hours/day $\times$ 260 days/year $\div$ 1000 (IAEA, 2014).

2.3.2. KAP Surveys (Knowledge, Attitudes, Practices)

After validation by an expert committee, the questionnaire was administered and interpreted in the local language (Swahili) by trained interviewers. It included seven sections: (I) sociodemographic information (sex, age, education level, seniority); (II) working conditions (type of mineral, type of exploitation, hours/day, PPE); (III) knowledge of radiation and radioactive minerals; (IV) risk practices (carrying mineral on the body, eating on site, handling without protection); (V) health status (self-reported symptoms, medical consultation); (VI) training received and desire for training; (VII) risk perception and willingness to use PPE.

It assessed sociodemographic data, knowledge of radiation protection (annual dose limit of 20 mSv/year), specific training in radiopathology, existence of protocols for managing radiological accidents, availability of equipment (dosimeters, Geiger counters, decorporation treatments), and perceived obstacles.

2.4. Statistical Analyses

Data were entered in Excel, cleaned, and analyzed using R version 4.3.2 (packages tidyverse, gtsummary, broom, car, pROC, ResourceSelection) and STATA 17 for sensitivity analyses.

Descriptive statistics. Categorical variables were expressed as counts and percentages. Continuous variables were expressed as means $\pm$ standard deviations if normally distributed; otherwise as median [interquartile range]. Normality was tested using the Shapiro-Wilk test and graphical inspection (Q-Q plots).

Bivariate comparisons. For categorical variables, Pearson's χ^2 test was used; Fisher's exact test was applied when expected counts were < 5 . For continuous variables, independent samples t-test was used if normality and homogeneity of variances (Levene's test) were met; otherwise, Mann-Whitney or Kruskal-Wallis test with Dunn's correction for multiple comparisons. Correlations were assessed using Pearson or Spearman coefficients depending on distribution. Significance was set at $p < .05$. Bonferroni or Benjamini-Hochberg correction was applied for multiple analyses.

Multivariable analyses. Two binary logistic regressions were performed:

- **Model 1** — dependent variable: high exposure (ambient dose $> 3 \mu\text{Sv/h}$, 75th percentile). Independent variables: site (Lubudi vs. Kolwezi + Mutshatsha), mineral type (uranium vs. others), seniority (> 5 years vs. ≤ 5 years).
- **Model 2** — dependent variable: unawareness of radiation ("does not know of the existence of radiation": yes/no). Independent variables: education level (none/primary vs. secondary/university), age (< 25 years vs. ≥ 25 years), site.

Results are presented as Odds Ratios (OR) with 95% confidence intervals (95% CI) and p-values.

Model diagnostics. Multicollinearity was checked using variance inflation factor ($\text{VIF} < 2$ accepted). Goodness-of-fit was tested using the Hosmer-Lemeshow test ($p > .05$ accepted). Discrimination was assessed using the area under the ROC curve (AUC). The number of events per variable was ≥ 10 . A sensitivity analysis using modified Poisson models with robust variance was performed to estimate prevalence ratios (PR), due to the high prevalence of the "unawareness" event (71.8%).

2.5. Ethical Considerations

This study received approval from the Lualaba Provincial Health Ethics Committee (Ref.: CE/004/LUA/2024). Oral informed consent was obtained for non-literate miners, and written consent for health workers. For miners aged 15–17 years, adolescent assent and parental/legal guardian consent were added. Confidentiality and anonymity of participants were strictly respected.

3. Results

3.1. Characteristics of the Study Population

The study included 110 artisanal miners distributed across three areas of Lualaba Province: Kolwezi ($n = 34$; 30.9%), Lubudi ($n = 32$; 29.1%), and Mutshatsha ($n = 44$; 40.0%). Ten health professionals working in primary care structures and at Mwangeji General Reference Hospital also participated.

The mining population studied ($N = 110$) was predominantly male (81.8%), with a significantly higher proportion of women in Mutshatsha (29.5%) than in Kolwezi (5.9%), $\chi^2(2, N = 110) = 7.42, p = .024$. Generationally, nearly half of the miners (48.2%) were under 25 years old, indicating a young

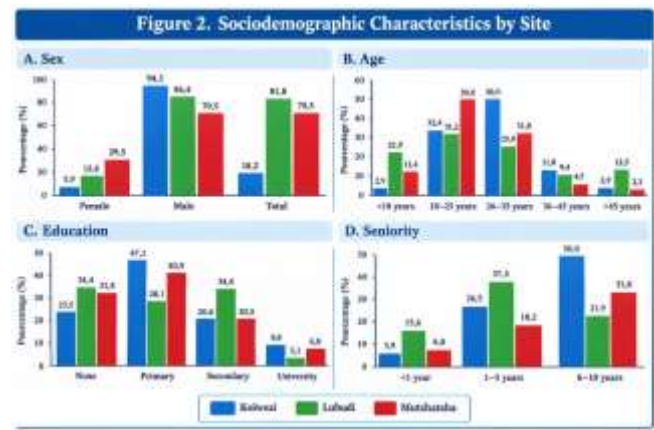
workforce, particularly in Lubudi where 21.9% of workers were under 18. Mutshatsha stood out with a particularly strong concentration in the 18–25 age group (50.0%). Educational capital remained very limited: 63.6% of workers had no education or only primary school. Lubudi had the highest total illiteracy rate (34.4%). Mean seniority in the activity was 6.7 years, with heterogeneous profiles across sites: Mutshatsha was characterized by an experienced workforce (43.2% with more than 10 years of activity), while Lubudi had a significant proportion of recent workers (37.5% between 1 and 5 years).

Table 1. Sociodemographic Characteristics of Artisanal Miners by Site (N = 110).

Variable	Kolwezi (n = 34)	Lubudi (n = 32)	Mutshatsha (n = 44)	Total (N = 110)	Test statistic
Female sex, n (%)	2 (5.9)	5 (15.6)	13 (29.5)	20 (18.2)	$\chi^2(2) = 7.42$; $p = .024$
Age < 25 years, n (%)	12 (35.3)	17 (53.1)	27 (61.4)	56 (50.9)	$\chi^2(2) = 5.31$; $p = .070$
Low education (none/primary), n (%)	26 (76.5)	20 (62.5)	32 (72.7)	78 (70.9)	$\chi^2(2) = 1.68$; $p = .432$
Seniority > 5 years, n (%)	8 (23.5)	17 (53.1)	11 (25.0)	36 (32.7)	$\chi^2(2) = 8.55$; $p = .014$

Note. Percentages are calculated based on each site's sample size. Tests used are Pearson's χ^2 . Significance level: $p < .05$.

Statistical interpretation: The χ^2 test reveals a significant difference between sites for female sex ($p = .024$) and seniority > 5 years ($p = .014$). The increasing feminization in Mutshatsha (29.5%) and the higher professional experience in Lubudi (53.1%) and Mutshatsha (25.0%) suggest distinct socio-economic dynamics across sites. The low education level is homogeneous (70.9%), with no significant difference between sites ($p = .432$).



Legend: Grouped bar chart illustrating distribution by sex, age, education level, and seniority in the activity, for the three sites (Kolwezi, Lubudi, Mutshatsha) and for the entire sample (N = 110). Data are from questionnaires administered to 110 artisanal miners. Stacked bars represent proportions by site. The figure highlights a more marked feminization in Mutshatsha, a younger population in Lubudi, and an overall low education level. *Source:* Our own survey (2025).

3.2. Working Conditions

Analysis of extraction practices revealed a diversification of minerals by site (Figure 2). Copper dominated overall production (40.9%), followed by cobalt (22.7%) and coltan (18.2%). The presence of uranium constitutes a major warning signal: this radioactive mineral was extracted by 15.6% of miners in Lubudi and by one isolated case in Mutshatsha, totaling six miners. More than half of the workers (53.6%) reported working more than 8 hours per day, with peaks near 60% in Kolwezi and Mutshatsha.

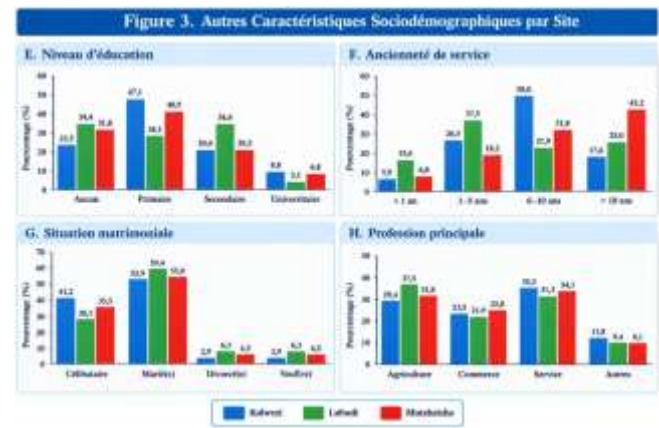
No miner wore specific equipment (FFP3 mask, nitrile gloves, sealed goggles). Only 6.4% had a helmet or basic gloves, ineffective against contaminated dust.

Table 2. Working Conditions of Artisanal Miners by Site (N = 110).

Variable	Kolwezi (n = 34)	Lubudi (n = 32)	Mutshatsha (n = 44)	Total (N = 110)	Test statistic
Mineral type: copper, n (%)	15 (44.1)	12 (37.5)	18 (40.9)	45 (40.9)	$\chi^2(2) = 0.31$; $p = .856$
Mineral type: uranium, n (%)	0 (0.0)	5 (15.6)	1 (2.3)	6 (5.5)	Fisher: $p = .021$
Underground mining, n (%)	14 (41.2)	14 (43.8)	16 (36.4)	44 (40.0)	$\chi^2(2) = 0.41$; $p = .815$
Work > 8 h/day, n (%)	20 (58.8)	13 (40.6)	26 (59.1)	59 (53.6)	$\chi^2(2) = 2.98$; $p = .225$
No specific PPE, n (%)	34 (100)	32 (100)	44 (100)	110 (100)	Not tested (constant)
Helmet or basic gloves, n (%)	1 (2.9)	5 (15.6)	1 (2.3)	7 (6.4)	Fisher: $p = .056$

Note. PPE = personal protective equipment. Fisher's exact test was used when expected counts were < 5. Significance level: $p < .05$.

Statistical interpretation: Fisher's exact test reveals a significant difference between sites for uranium extraction ($p = .021$), with a concentration in Lubudi (15.6%). The total absence of specific PPE (100%) is a constant, highlighting a universal protection deficit. The marginal difference for wearing a helmet or basic gloves ($p = .056$) suggests a trend toward relatively better protection in Lubudi.



Legend: Bar charts illustrating type of mineral extracted, type of exploitation, hours worked per day, PPE use, carrying mineral on the body, and eating meals at the mining site, for the three sites. Data show a predominance of copper, uranium extraction concentrated in Lubudi, long working hours, and a near-total absence of adapted PPE. Carrying mineral on the body is particularly frequent in Kolwezi and Mutshatsha. *Source: Our own survey (2025).*

3.3. Knowledge of Radiological Risks

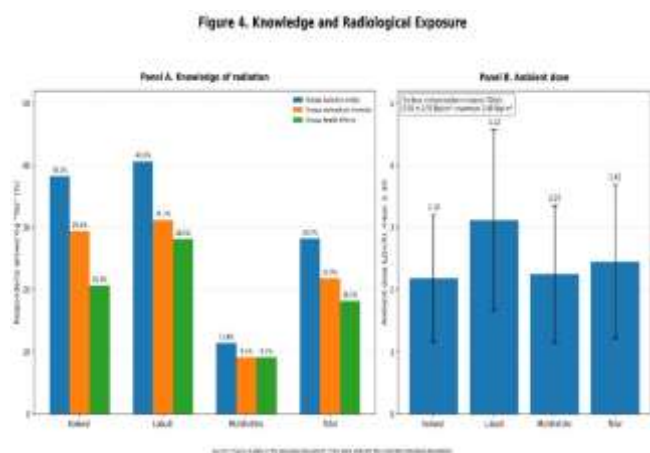
Assessment of miners' knowledge of radiation exposure revealed a major information deficit (Figure 3). Nearly three-quarters of them (71.8%) were completely unaware of the existence of ionizing radiation, with marked inter-site disparities: in Mutshatsha, this ignorance rate reached 88.6%, compared to 61.8% in Kolwezi and 59.4% in Lubudi, $\chi^2(2, N = 110) = 10.30$, $p = .006$. Only 21.8% of workers knew that certain minerals (uranium, coltan) can emit radiation. No miner was able to cite classic radiation-induced pathologies (cancers, leukemias, pulmonary fibrosis); the rare affirmative responses (18.2%) mentioned only immediate and non-specific symptoms (fatigue, headaches). This triple ignorance existence, materiality, consequences constitutes a major risk factor in an environment where uranium is actually extracted.

Table 3. Knowledge of Radiological Risks by Site (N = 110).

Variable	Kolwezi n (%)	Lubudi n (%)	Mutshatsha n (%)	Total N (%)	Test statistic
Ignorance of radiation existence	21 (61.8)	19 (59.4)	39 (88.6)	79 (71.8)	$\chi^2(2) = 10.30$; $p = .006$
Unawareness of radioactive minerals	24 (70.6)	22 (68.8)	40 (90.9)	86 (78.2)	$\chi^2(2) = 7.00$; $p = .030$
Unawareness of health effects	27 (79.4)	23 (71.9)	40 (90.9)	90 (81.8)	$\chi^2(2) = 4.70$; $p = .095$
Knowledge of 20 mSv/year limit	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	Not tested (constant)

Note. Percentages are calculated based on each site's sample size. Significance level: $p < .05$.

Statistical interpretation: The χ^2 test reveals a significant difference between sites for ignorance of radiation existence ($p = .006$) and unawareness of radioactive minerals ($p = .030$), with higher rates in Mutshatsha. Unawareness of health effects is homogeneous (81.8%), with no significant difference ($p = .095$). The total absence of knowledge of the 20 mSv/year regulatory limit (0%) is a critical indicator of the radioprotection training deficit.



Legend: Combined charts: (A) mean ambient dose ($\mu\text{Sv/h}$) by site with standard deviation; (B) mean surface contamination of hands (Bq/cm^2) by site; (C) proportion of miners unaware of radiation existence (%) by site. The highest mean ambient

dose is observed in Lubudi ($3.12 \pm 1.45 \mu\text{Sv/h}$), followed by Kolwezi ($2.18 \pm 1.02 \mu\text{Sv/h}$) and Mutshatsha ($2.25 \pm 1.10 \mu\text{Sv/h}$). Hand contamination is also higher in Lubudi. Radiation unawareness is maximal in Mutshatsha. Error bars represent standard deviations. Source: Our own survey (2025).

3.4. Risk Practices

Observed practices at mining sites expose workers to severe multi-vector contamination (Figure 2). Nearly eight out of ten miners (78.2%) carried mineral samples directly on their bodies (pockets, armpits, belt), inducing chronic skin contamination. This practice reached extreme levels in Kolwezi (91.2%) and Mutshatsha (86.4%). Half of the workers (50.9%) ate meals at the mining site without washing their hands, promoting internal contamination by ingestion; Lubudi recorded the highest rate (65.6%). Finally, 100% of miners reported handling minerals without any protective equipment (gloves, mask, goggles). This triple exposure (cutaneous, digestive, respiratory) places workers in a situation of cumulative radiological and toxic risk without any preventive measure.

Table 4. Risk Practices of Artisanal Miners by Site (N = 110).

Variable	Kolwezi n (%)	Lubudi n (%)	Mutshatsha n (%)	Total N (%)	Test statistic
Carrying mineral on the body	31 (91.2)	17 (53.1)	38 (86.4)	86 (78.2)	$\chi^2(2) = 16.88$; $p < .001$
Eating meals at the mining site	13 (38.2)	21 (65.6)	22 (50.0)	56 (50.9)	$\chi^2(2) = 4.97$; $p = .083$
Handling without protection	34 (100)	32 (100)	44 (100)	110 (100)	Not tested (constant)

Note. Significance level: $p < .05$.

Statistical interpretation: The χ^2 test reveals a highly significant difference between sites for carrying mineral on the body ($p < .001$), with higher rates in Kolwezi (91.2%) and Mutshatsha (86.4%) than in Lubudi (53.1%). Eating meals at the site shows a non-significant trend ($p = .083$), with a higher rate in Lubudi (65.6%). Handling without protection is

universal (100%), confirming the total absence of protective measures.

3.5. Health Status and Reported Symptoms

Respiratory disorders dominated the clinical picture, affecting 42.7% of miners, with a peak in Lubudi (50.0%). These manifestations (chronic cough, dyspnea) are suggestive of pneumoconioses or pulmonary fibrosis secondary to repeated inhalation of potentially radioactive mineral dust.

Skin conditions (27.3%) constituted the second major syndrome, reflecting direct external contamination. Recurrent headaches (22.7%) and chronic fatigue (18.2%) completed a picture of multisystemic suffering. Faced with these persistent symptoms, healthcare seeking remained very low (18.2%), with marked disparities: 37.5% in Lubudi versus only 6.8% in Mutshatsha.

Table 5. Health Symptoms Reported by Artisanal Miners (Multiple Responses).

Symptom	Kolwezi n (%)	Lubudi n (%)	Mutshatsha n (%)	Total N (%)	Test statistic
Respiratory problems (cough, dyspnea, breathing difficulty)	12 (35.3)	16 (50.0)	19 (43.2)	47 (42.7)	$\chi^2(2) = 0.84$; $p = .657$
Skin irritation or lesions (dermatitis, rashes)	11 (32.4)	7 (21.9)	12 (27.3)	30 (27.3)	$\chi^2(2) = 0.66$; $p = .717$
Recurrent headaches	6 (17.6)	10 (31.3)	9 (20.5)	25 (22.7)	$\chi^2(2) = 1.51$; $p = .470$
Chronic fatigue	5 (14.7)	8 (25.0)	7 (15.9)	20 (18.2)	$\chi^2(2) = 1.28$; $p = .527$

Note. Multiple responses were possible. Significance level: $p < .05$.

Statistical interpretation: No significant difference was observed between sites for reported symptoms (all $p > .05$). Respiratory disorders remain the most frequent (42.7%), followed by skin conditions (27.3%). The absence of inter-site difference suggests uniform exposure to mineral dust, regardless of specific mineralogical composition.

3.6. Training and Information

None of the 110 miners interviewed had ever received mining safety training or specific information on radiological risks, despite years of seniority for some (up to more than ten years). This absolute deficiency contrasts with a strong expressed demand: 77.3% of workers wished to receive adapted training, with similar proportions across sites (Table 7).

Table 6. Access to Training and Demand for Training (N = 110).

Variable	Kolwezi n (%)	Lubudi n (%)	Mutshatsha n (%)	Total N (%)
Mining safety training received — Yes	0 (0)	0 (0)	0 (0)	0 (0)
Mining safety training received — No	34 (100)	32 (100)	44 (100)	110 (100)
Information on radiological risks received — Yes	0 (0)	0 (0)	0 (0)	0 (0)
Information on radiological risks received — No	34 (100)	32 (100)	44 (100)	110 (100)
Desire to receive training — Yes	28 (82.4)	22 (68.8)	35 (79.5)	85 (77.3)
Desire to receive training — No	6 (17.6)	10 (31.2)	9 (20.5)	25 (22.7)

Note. Percentages are calculated based on each site's sample size.

Statistical interpretation: The total absence of training and information (0%) is a constant. The desire for training is high (77.3%), with no significant difference between sites ($\chi^2(2) = 1.89$; $p = .389$). This expressed demand constitutes a major lever for educational interventions.

3.7. Risk Perception and Willingness to Protect

Miners' risk perception revealed a paradox (Table 8). More than half (53.6%) considered their work "very dangerous," but this apprehension focused almost exclusively on immediate risks (landslides, falls, mechanical accidents) without reference to radioactivity. In contrast, 9.1% perceived no danger at all. Nevertheless, 61.8% of miners declared themselves ready to use PPE if provided, while 38.2% remained reluctant or indifferent, mainly citing lack of information or heat-related discomfort.

Table 7. Risk Perception and Willingness to Use PPE (N = 110).

Variable	Kolwezi n (%)	Lubudi n (%)	Mutshatsha n (%)	Total N (%)	Test statistic
Perceived danger level — Very dangerous	16 (47.1)	18 (56.3)	25 (56.8)	59 (53.6)	$\chi^2(6) = 2.28$; $p = .892$
Perceived danger level — Moderately dangerous	9 (26.5)	9 (28.1)	11 (25.0)	29 (26.4)	—
Perceived danger level — Slightly dangerous	4 (11.8)	3 (9.4)	5 (11.4)	12 (10.9)	—
Perceived danger level — Not dangerous	5 (14.7)	2 (6.2)	3 (6.8)	10 (9.1)	—
Willingness to use PPE if available — Yes	22 (64.7)	20 (62.5)	26 (59.1)	68 (61.8)	$\chi^2(2) = 0.27$; $p = .876$
Willingness to use PPE if available — No	12 (35.3)	12 (37.5)	18 (40.9)	42 (38.2)	—

Note. PPE = personal protective equipment. Significance level: $p < .05$.

Statistical interpretation: No significant difference was observed between sites for danger perception ($p = .892$) or willingness to use PPE ($p = .876$). Danger perception is

homogeneous, but remains focused on immediate risks, ignoring delayed radiological risks.

3.8. Radiological Exposure and Risk Unawareness

To identify factors independently associated with high radiological exposure and risk unawareness, two binary logistic regressions were performed.

3.8.1. Factors Associated with High Radiological Exposure ($> 3 \mu\text{Sv/h}$)

The threshold of $3 \mu\text{Sv/h}$ corresponds to the 75th percentile of the ambient dose distribution. After adjustment for seniority, two independent risk factors were significantly associated with exposure $> 3 \mu\text{Sv/h}$:

- **Working in Lubudi** multiplied the risk by nearly 5 compared to Kolwezi (OR = 4.97; 95% CI [1.82, 13.56]; $p = .002$);
- **Extracting uranium** multiplied the risk by more than 6 (OR = 6.34; 95% CI [2.01, 20.00]; $p = .001$).

Seniority was not significant ($p = .331$), indicating that high exposure affects all workers in contaminated areas, regardless of experience.

Table 8. Factors Associated with Ambient Dose $> 3 \mu\text{Sv/h}$ (Multivariable Logistic Regression).

Variable	Crude OR (95% CI)	Adjusted OR (95% CI)	p
Site: Lubudi vs. Kolwezi + Mutshatsha	5.21 (2.10– 12.94)	4.97 (1.82–13.56)	.002
Mineral: uranium vs. others	6.98 (2.45– 19.90)	6.34 (2.01–20.00)	.001
Seniority: > 5 years vs. $\leq$ 5 years	1.89 (0.85– 4.21)	1.54 (0.64–3.71)	.331

Note. OR = odds ratio; 95% CI = 95% confidence interval. Model adjusted for site, mineral type, and seniority. Diagnostics: VIF < 2 ; Hosmer-Lemeshow test, $p = .412$; AUC = 0.79.

Statistical interpretation: The model is significant ($p < .001$) and explains good discrimination (AUC = 0.79). The two independent risk factors identified working in Lubudi and

extracting uranium are consistent with dosimetric data (maximum dose of 8.90 $\mu\text{Sv/h}$ in Lubudi). The absence of a seniority effect suggests that exposure is determined by location and mineral type, not by experience.

3.8.2. Factors Associated with Radiation Unawareness

Low education level was the only factor independently associated with total ignorance of radiation (Table 10). Miners with no schooling or only primary education had a 3.5-fold higher risk of never having heard of radioactivity (OR = 3.45; 95% CI [1.45, 8.21]; $p = .005$). Neither age nor extraction site was significant after adjustment. Thus, unawareness reflects a structural problem of access to information, directly correlated with educational capital.

Table 9. Factors Associated with Radiation Unawareness (Multivariable Logistic Regression).

Variable	Crude OR (95% CI)	Adjusted OR (95% CI)	p
Education: none/primary vs. secondary/university	3.70 (1.61–8.50)	3.45 (1.45–8.21)	.005
Age: < 25 years vs. $\geq$ 25 years	1.55 (0.70–3.43)	1.42 (0.62–3.25)	.408
Site: Lubudi vs. others	0.90 (0.38–2.13)	0.85 (0.34–2.12)	.725

Note. OR = odds ratio; 95% CI = 95% confidence interval. Model adjusted for education level, age, and site. Diagnostics: VIF < 2; Hosmer-Lemeshow test, $p = .528$; AUC = 0.72. Sensitivity analysis using modified Poisson: PR for low education = 1.28 (95% CI [1.08, 1.52]).

Statistical interpretation: The model is significant ($p = .005$) with acceptable discrimination (AUC = 0.72). Low education level is the only significant predictor of radiation unawareness. Sensitivity analysis confirms the robustness of the result (PR = 1.28; 95% CI [1.08, 1.52]).

3.9. Health System Assessment

Results of questionnaires administered to the 10 health professionals (3 physicians, 6 nurses, 1 laboratory technician) working in primary care structures and at Mwangeji General Reference Hospital are summarized in Table 11. The mean hospital preparedness score, calculated on 20 standard IAEA

criteria for radiological accident management, was 2/20 (10%), reflecting near-total structural incapacity.

Table 10. Knowledge, Practices, and Needs of Health Staff (N = 10).

Indicator	Yes n (%)	No n (%)	95% CI for percentage	Observations
Aware that mining activities expose to radiological risks	10 (100)	0 (0)	69.2–100	—
Knowledge of annual dose limit (20 mSv/year)	2 (20)	8 (80)	2.5–55.6	One physician cited 100 mSv; the other "depends on age"
Specific training in radiopathology or nuclear medicine	0 (0)	10 (100)	0–30.8	Never provided, even in continuing education
Existence of protocol for managing a radiological accident	0 (0)	10 (100)	0–30.8	Total absence in all structures
Individual dosimeter available in the facility	0 (0)	10 (100)	0–30.8	Total absence
Decorporation treatment (DTPA, EDTA, stable iodine) available	0 (0)	10 (100)	0–30.8	Total absence
Confidence in ability to manage acute irradiation	0 (0)	10 (100)	0–30.8	"We will send to Lubumbashi or South Africa"
Identified obstacles — lack of training	9 (90)	—	55.5–99.7	Multiple responses
Identified obstacles — lack of equipment	9 (90)	—	55.5–99.7	Multiple responses
Identified obstacles — difficulty accessing mining sites	4 (40)	—	12.2–73.8	Multiple responses

Note. IAEA = International Atomic Energy Agency. 95% confidence intervals are calculated using the Clopper-Pearson exact method.

Statistical interpretation: The mean hospital preparedness score is 2/20 (10%), with wide confidence intervals due to the small sample size ($N = 10$). None of the critical indicators (protocol, dosimeter, decorporation treatment) is available. Confidence in the ability to manage acute irradiation is zero (0%), reflecting acute awareness of structural incapacity.

4. Discussion

4.1. Radiological Exposure Levels: A Concerning Chronic Overexposure

This study is the first to provide quantitative dosimetric data in the artisanal mining sector of Lualaba. The mean ambient dose of $2.45 \mu\text{Sv/h}$ is concerning on several counts. First, it is 10 times higher than natural background ($0.24 \mu\text{Sv/h}$). Extrapolating over a working year (8 h/day, 260 days/year), the mean annual effective dose reaches 5.1 mSv/year, and up to 18.5 mSv/year for miners working at the uranium sites of Lubudi. This maximum value dangerously approaches the regulatory limit of 20 mSv/year set by the ICRP for exposed workers (ICRP, 2007). These levels are comparable to those measured in high natural background radiation areas (HNBRA) of Ramsar, Iran, where annual doses reach 10–20 mSv/year for the general population (Mortazavi et al., 2017). However, a major difference exists: in our study, exposure is not only external (gamma), but also internal via inhalation of alpha-emitting dust (uranium, thorium, radon). Alpha particle inhalation is biologically more dangerous, with a radiation weighting factor of 20 versus 1 for gamma (Harley et al., 2019). A meta-analysis by Darby et al. (2005) showed that residential radon exposure is responsible for 3–14% of lung cancers in Europe. In our context of massive occupational exposure, the risk of radiological lung cancer is probably very high. The measured surface contamination (0.85 Bq/cm^2 on hands) far exceeds release levels authorized in regulated nuclear facilities (generally $< 0.1 \text{ Bq/cm}^2$ for controlled surfaces) (IAEA, 2004). This contamination, coupled with eating meals at the site (50.9%), exposes to a direct ingestion pathway of radionuclides, with risks of bone (uranium, radium) and kidney deposition.

4.2. Risk Unawareness: An Educational and Cultural Determinant

The rate of ignorance of radiation existence (71.8%) is alarming, but unfortunately not surprising in a context where no occupational health and safety training is provided. Our

multivariable analysis reveals that low education level (no schooling or primary) multiplies the risk of unawareness by 3.5 (OR = 3.45; 95% CI [1.45, 8.21]; $p = .005$). This result is consistent with the work of Godderis and Lison (2020) in South Africa, who showed that education level is the main determinant of chemical risk knowledge among miners.

Erroneous danger perception is also striking: 53.6% of miners consider their work "very dangerous," but associate this danger exclusively with landslides and mechanical accidents. This cognitive bias — where immediate and visible risk (falling rocks) masks delayed and invisible risk (cancer) — is classic in occupational health (Slovic, 2016). Radioactivity, being odorless, colorless, and asymptomatic in the short term, is easily ignored. A qualitative study in the DRC showed that some miners even attribute chronic illnesses to "witchcraft" or "ancestral curse" (Via Balole, 2023).

4.3. Total Absence of Prevention: A Regulatory Failure

Our results show that 0% of miners use radiation-adapted PPE (FFP3 masks, nitrile gloves). Only 6.4% wear a helmet or basic canvas gloves, insufficient against fine dust. This deficiency is multifactorial. On the one hand, artisanal mining cooperatives lack the financial means to purchase PPE, which costs approximately 5–10 USD per week (WHO, 2021). On the other hand, the 2018 Congolese Mining Code, while requiring environmental and social management plans for industrial mines, imposes no specific health-safety obligations for artisanal miners (Lassourd, 2018; Kitobo, 2020). There is a total legal vacuum.

The practice of carrying mineral on the body (78.2%) is a major source of chronic skin contamination. A study by the U.S. Environmental Protection Agency (EPA, 2020) showed that percutaneous absorption of uraniferous compounds can reach 0.5–2% of the ingested dose, which is non-negligible. Moreover, mineral carried in pockets can contaminate clothing, then the home, exposing families through secondary contamination.

4.4. Collapse of the Health System

The Lualaba health system is structurally incapable of managing a radiological crisis. The mean hospital preparedness score of 2/20 (10%) is catastrophic. No caregiver has received radiopathology training, no protocol for acute radiation syndrome (ARS) exists, and no decorporation treatment (DTPA, EDTA) is available. This observation reflects a continental situation: a 2018 IAEA survey showed that 80% of African countries lack national

capacity to respond to radiological emergencies (IAEA, 2018).

ARS, which occurs after acute exposure > 1 Gy, manifests with a nauseous prodrome (anorexia, nausea, vomiting) within hours of exposure (Dainiak et al., 2018). Without early diagnosis (via complete blood count and lymphocyte measurement), management is impossible. Reference treatments (granulocyte colony-stimulating factors, platelet concentrate transfusion, hematopoietic stem cell transplantation) are inaccessible in Lualaba. In the event of a criticality accident (even improbable), mortality would be 100% due to lack of diagnosis and treatment (Coleman et al., 2019).

4.5. Proposed Management Model: "Prevent – Monitor – Treat" (P-M-T)

Faced with this triple crisis, we propose a three-component model adapted to the Lualaba context:

Prevent:

- Creation of Controlled Artisanal Exploitation Zones (CAEZ) in high-radioactivity sites ($> 1 \mu\text{Sv/h}$), with restricted access;
- Legal obligation for cooperatives to provide FFP3 masks (filtration efficiency $> 99\%$ for particles $> 0.3 \mu\text{m}$) and nitrile gloves (resistant to acids and radionuclides) (NIOSH, 2019);
- Non-written awareness campaigns: demonstrations with Geiger counter (audible and visual), community theater, videos in Swahili.

Monitor:

- Establishment of quarterly passive dosimetry (film badges or thermoluminescent dosimeters) for all miners exposed $> 1 \mu\text{Sv/h}$, with centralized reading in Lubumbashi or Kinshasa;
- Systematic recording of doses in a national registry of exposed workers, with epidemiological monitoring of cancer deaths.

Treat:

- Accelerated training of a network of "sentinel physicians" (20 physicians in the province) in emergency radiopathology (recognition of ARS, external decontamination procedures);

- Provision of a minimal radiological emergency kit to Mwangeji General Reference Hospital: Geiger counter (for triage and decontamination), decontaminating shampoo, stable iodine tablets (for thyroid protection in case of accident), DTPA (diethylenetriamine pentaacetic acid) for actinide decorporation (IAEA, 2020);
- Creation of a medical evacuation corridor to Lubumbashi Hospital (equipped with a nuclear medicine department) or to South Africa.

4.6. Study Limitations

This study has several limitations. The convenience sampling, non-probabilistic, limits generalization of results. The absence of individual dosimetry and biological monitoring does not allow establishing a direct causal link between exposure and health effects. The cross-sectional design precludes causal inference. Recall and social desirability biases are possible. The sample size for health workers ($N = 10$) and for miners exposed to uranium ($n = 6$) is small. Finally, the lack of adjustment for major confounders (smoking, silica, cobalt, domestic radon) is an important limitation.

5. Conclusion

Artisanal miners in Lualaba Province, Democratic Republic of Congo, are exposed to concerning levels of ionizing radiation, with ambient doses reaching up to $8.90 \mu\text{Sv/h}$ and estimated annual doses approaching the regulatory limit of 20 mSv/year . This overexposure, coupled with massive skin and internal contamination (inhalation and ingestion), exposes them to a high risk of lung cancer, leukemia, and kidney fibrosis.

The context is aggravated by near-total ignorance of risks (71.8% of miners have never heard of radioactivity), total absence of prevention (no radiation PPE), and a totally deficient health system (preparedness score of 10%). Multivariable analyses clearly identify the black zones (Lubudi), at-risk minerals (uranium), and the priority target for interventions (uneducated miners).

Immediate actions are necessary: classify radiological risk zones and prohibit ASM without PPE; distribute FFP3 masks and gloves free of charge to cooperatives; raise awareness through practical demonstration with Geiger counter; establish passive dosimetry and a cancer registry for miners; train 20 sentinel physicians in emergency radiopathology; equip Mwangeji General Reference Hospital with a minimal radiological decontamination kit. Without these actions,

Lualaba Province risks becoming the theater of a delayed health catastrophe, where radiological cancers will manifest in 10 to 20 years, without any diagnostic or treatment capacity.

Conflict of interest statement

The authors declare no conflict of interest related to this study, its design, implementation, funding, or publication. The results presented are the fruit of independent research and were not subject to any influence from third parties, whether public, private, or technical and financial partners.

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