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Radiation Pollution and Public Health Impacts in Mailuu-Suu, Kyrgyzstan

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ABSTRACT

This study investigates the critical issue of radiation contamination in Mailuu-Suu, Kyrgyzstan, a legacy of extensive uranium mining and milling operations during the Soviet era. The research centers on the environmental behavior and health impacts of radon-222 and associated radionuclides emanating from uranium mill tailings. A comprehensive year-long indoor radon monitoring program (July 2001–July 2002) revealed radon concentrations that substantially exceeded the national Radiation Safety Standards (RSS-96), posing serious health risks to local populations. Approximately 1.9 million cubic meters of uranium mill tailings, distributed across multiple unsecured waste dumps, were assessed for their radiological burden. While precise activity levels remain undocumented, it is estimated that these tailings represent tens of thousands of tonnes of radioactive material. Based on typical uranium ore residue densities and grades, this volume could contain over 3–5 million tonnes of material, with estimated activities ranging from 10^{13} to 10^{15} becquerels, depending on radionuclide composition. Epidemiological data indicate elevated rates of cancer, respiratory illnesses, and congenital anomalies, particularly among vulnerable groups such as children, pregnant women, and the elderly. The findings highlight an urgent

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ARTICLE INFO

Received: 19 June 2025 | Revised: 4 August 2025 | Accepted: 6 August 2025 | Published Online: 29 August 2025

DOI: https://doi.org/10.30564/jees.v7i8.10588

CITATION

Egemberdieva, A.D., Kamchybekova, K.D., Abdulmitalipovna, M.N., et al., 2025. Radiation Pollution and Public Health Impacts in Mailuu-Suu, Kyrgyzstan. Journal of Environmental & Earth Sciences. 7(8): 363–375. DOI: https://doi.org/10.30564/jees.v7i8.10588

need for targeted environmental remediation, continuous radiological surveillance, and public health strategies to mitigate long-term risks and enhance ecological and human safety in the region.

Keywords: Radiation Pollution; Radon-222; Mailuu-Suu; Public Health; Uranium Mining; Radioactive Waste; Environmental Monitoring; Kyrgyzstan

1. Introduction

The historical context of uranium mining in Mailuu-Suu presents a unique intersection of geopolitical, environmental, and health dynamics. During the Soviet era, the strategic importance of uranium production led to accelerated industrial operations with minimal regard for long-term environmental consequences. As a result, modern Mailuu-Suu faces the compounded burden of radioactive contamination embedded within its infrastructure and landscape. Despite various international and national initiatives aimed at assessing and mitigating the effects, the sheer scale of contamination and the complexity of tailings management continue to hinder effective remediation. Scientific investigations into uranium mining legacies, particularly in Central Asia, have increasingly emphasized the need for integrating multidisciplinary approaches. This includes not only geological and radiological assessments but also socioeconomic evaluations and community engagement strategies. Mailuu-Suu serves as a microcosm for similar post-industrial sites across the globe, where environmental justice, health equity, and sustainable development intersect. The present study, therefore, contributes not only to local knowledge but also to the global discourse on managing hazardous legacies from extractive industries.

Mailuu-Suu, located in the Jalal-Abad Province of southeastern Kyrgyzstan, served as a critical center for uranium mining and processing from 1946 to 1968, leaving behind a complex legacy of environmental degradation and public health challenges [1]. The industrial activities of this period resulted in the accumulation of approximately 1.9 million cubic meters of radioactive mill tailings, distributed across 23 tailings dams and 13 waste rock dumps, which continue to pose significant risks to the region's ecosystem and its inhabitants [2]. These tailings, situated on tectonically unstable slopes, contain hazardous radionuclides, including uranium-238, radium-226, and thorium-232, which release radon-222, a radioactive gas recognized globally for its carcinogenic properties [3]. The Mailuu-Suu River, a vital regional water resource and a key tributary of the Syr Darya, is severely contaminated with heavy metals and radioactive isotopes, amplifying ecological damage and threatening the health of communities downstream that rely on the river for drinking water, irrigation, and other essential uses [4]. This contamination not only disrupts the region's biodiversity but also undermines the livelihoods of local populations dependent on agriculture and fisheries.

Radon-222, a decay product of uranium-238, is a major global health concern, identified as the second leading cause of lung cancer, particularly in environments with inadequate ventilation [5]. In Mailuu-Suu, the situation is exacerbated by the use of contaminated materials in construction and the proximity of residential areas to tailings sites, which significantly elevate indoor radon concentrations and heighten exposure risks for residents [6]. The region's geologically dynamic environment, characterized by frequent seismic activity and landslides, further compounds the potential for catastrophic failures of tailings dams. A notable example is the 1958 incident, during which 600,000 cubic meters of radioactive waste were released into the Mailuu-Suu River, causing widespread environmental contamination and long-term ecological damage [7]. This study provides a detailed quantification of the mass and radiological activity of the 1.9 million cubic meters of uranium mill tailings, integrating these findings into a comprehensive evaluation of their environmental and public health impacts. This analysis aims to elucidate the scope of the hazards and inform the development of targeted remediation strategies.

1.1. Objectives and Scope

The objectives of this research are fourfold: (1) to systematically measure and analyze radon-222 concentrations in residential buildings to assess exposure levels and associated health risks, (2) to characterize the radiological composition and activity of uranium mill tailings to better understand their hazard potential, (3) to evaluate the public health consequences, with a particular focus on vulnerable demographic groups such as children, the elderly, and those with pre-existing health conditions, and (4) to propose evidence-based mitigation strategies to address the identified environmental and health risks. This study focuses on Mailuu-Suu as a critical example of a uranium legacy site, drawing on data from a radon monitoring initiative (July 2001–July 2002), health surveys, and environmental assessments to highlight the region's challenges and inform policy. These datasets provide critical insights into the scale of the crisis in Mailuu-Suu, highlighting the urgent need for coordinated interventions to mitigate the intertwined environmental and public health challenges. While the data are from 2001–2002, they remain relevant due to the persistent nature of the radiological legacy and limited remediation progress in the region. By offering a rigorous foundation for informed policy decisions and remediation efforts, this research seeks to address the long-term impacts of Mailuu-Suu's uranium mining legacy, protecting the region's population and ecosystem from further harm.

2. Materials and Methods

2.1. Study Area

Mailuu-Suu is located within the tectonically dynamic Fergana Valley, a region characterized by significant geological instability due to its position along active fault lines. The area is encircled by extensive uranium mill tailings and waste dumps, remnants of intensive Soviet-era mining operations that have left a profound legacy of environmental degradation [1]. These tailings, comprising approximately 1.9 million cubic meters of radioactive material, are a primary source of radiological contamination, posing ongoing risks to both the environment and public health. Historically, the local economy of Mailuu-Suu was heavily reliant on the extraction of uranium, lead, and zinc, which drove economic activity during the Soviet period but resulted in widespread environmental pollution due to inadequate waste management practices [8]. The intensive mining activities have left behind a complex matrix of radionuclides and heavy metals that continue to compromise the ecological integrity of the region. A critical environmental concern is the contamination of the Mailuu-Suu River, a vital lifeline for both drinking water and agricultural activities in the region. The river is significantly polluted with radionuclides, such as radium-226 and uranium isotopes, as well as heavy metals, including lead and zinc, which originate from the leaching of nearby tailings and waste dumps [4]. This pollution not only affects the immediate vicinity of Mailuu-Suu but also poses substantial risks to downstream communities in Kyrgyzstan and Uzbekistan, where the river serves as a crucial resource for domestic and agricultural water supplies. The transboundary nature of this contamination underscores the broader regional implications of the radiological legacy, threatening water security, food safety, and public health across multiple jurisdictions.

2.2. Radon Monitoring

The primary source of indoor radon is the soil beneath the building. In such cases, radon infiltrates the interior through cracks and microfissures in the floors and structural joints. Rocks with elevated concentrations of radium and thorium may vary in type (e.g., granite, sand, clay, shale) and are not necessarily located at the surface.

Radon can migrate to the Earth's surface through several mechanisms:

- by diffusion,
- by mechanical or convective transport through fractures,
- by filtration of radon-enriched groundwater (particularly when uranium-bearing minerals are in contact with carbonate sedimentary formations).

Consequently, a low specific activity of surface soils does not inherently ensure low indoor radon concentrations. Direct measurement of radon levels within buildings is therefore essential.

To implement effective mitigation strategies and optimize resource allocation, it is critically important to delineate radon-prone zones. A study conducted by the Institute of Nuclear Physics of the Academy of Sciences of Uzbekistan found that radioactive contamination levels in the river during spring were twice as high as in summer, due to heavy rainfall washing radioactive waste from tailings ponds and landfills.

From July 2001 to July 2002, a comprehensive study was conducted to measure radon-222 concentrations in 34 residential buildings across Mailuu-Suu city and the neighboring villages of Sary-Bee and Yuzhny Karagach, located in the Jalal-Abad Province of southeastern Kyrgyzstan. Radon detectors supplied by Radon Safety Services Inc. (RSSI, USA) were utilized, employing advanced photoactive film technology designed to detect alpha particle emissions resulting from radon-222 decay [9]. Detectors were placed in residential buildings for a continuous three-month period to capture seasonal variations in radon concentrations. Following the exposure period, the detectors were retrieved and sent to the RSSI laboratory in the United States for analysis, where the photoactive films were processed to quantify alpha particle interactions, providing precise measurements of radon-222 levels. The results were converted from picoCuries per liter (pCi/L) to Becquerels per cubic meter (Bq/m^3) to align with Kyrgyzstan's RSS-96 radiation safety standards, which establish a maximum equivalent equilibrium volumetric activity (EEVA) limit of 200 Bq/m^3 for existing buildings and 100 Bq/m^3 for new constructions [10]. The methodology ensured robust data collection, with quality control measures including calibration of detectors and cross-verification with international standards.

2.3. Characterization of Uranium Mill Tailings

The radiological characteristics of the approximately 1.9 million cubic meters of uranium mill tailings were evaluated using data from established literature and regional studies [2,11]. An average density of 1.6 tonnes per cubic meter was applied to calculate the total mass, resulting in an estimated 3.04 million tonnes [12]. The activity content was derived by estimating concentrations of uranium-238, radium-226, and thorium-232, with specific activities calculated based on their decay chains. Data were sourced from the European Commission-TACIS project and regional environmental assessments [13].

2.4. Health Surveys

The health data for this study were systematically gathered through a multifaceted approach designed to comprehensively assess the radiation-related health impacts in the Mailuu-Suu region. Primary data collection involved structured interviews conducted with local health care providers, including physicians, nurses, and public health officials, to obtain qualitative insights into the prevalence and patterns of radiation-associated illnesses within the community. These interviews provided critical contextual information regarding the health challenges faced by residents, particularly in areas proximate to uranium mill tailings. They facilitated the identification of key morbidity trends observed in clinical practice [14]. In parallel, clinical examinations were performed on a cohort of women who had recently given birth in high-radiation zones within the Mailuu-Suu region. These examinations focused on assessing maternal and neonatal health outcomes in the context of chronic radiological exposure. Placental samples were collected from these participants and subjected to detailed laboratory analysis to quantify the concentrations of uranium and thorium isotopes, key radionuclides associated with the region's environmental contamination. Additional placental parameters, such as weight and thickness, were meticulously measured to evaluate potential correlations between radionuclide bioaccumulation and placental morphology, which could indicate disruptions in fetal development and maternal health [14]. These clinical and laboratory assessments provided robust evidence of the physiological impacts of radiological exposure on reproductive outcomes. Morbidity data were further compiled through a systematic review of local medical records, which offered a comprehensive dataset on the incidence of radiation-related health conditions across the broader population. These records documented elevated rates of various malignancies, including lung, stomach, and kidney cancers, as well as respiratory conditions such as chronic bronchitis and asthma, and cardiovascular diseases, all of which are potentially linked to chronic exposure to radionuclides and heavy metals.

Health data were gathered through structured interviews with local healthcare providers, clinical examinations of 70 women who had recently given birth in high-radiation zones, and a systematic review of local medical records. Placental samples were analyzed for uranium and thorium isotopes, with additional measurements of placental weight and thickness to assess correlations with radionuclide bioaccumulation [14]. Pearson correlation coefficients were calculated to evaluate the relationship between radon exposure and health outcomes, including cancer incidence and congenital anomalies. Medical records provided data on malignancies, respiratory diseases, cardiovascular conditions, and reproductive health outcomes, with a focus on vulnerable populations.

2.5. Data Analysis

Radon concentrations were compared against RSS-96 standards [10]. Descriptive statistics (mean, standard deviation) and Pearson correlation coefficients were used to summarize radon levels and explore associations with health outcomes. Multivariate regression models were applied to assess the impact of radon exposure, adjusting for confounders such as age and smoking status. Tailings activity data were validated against international studies [15].

3. Results

3.1. Radiation Safety Standards

Kyrgyzstan's Radiation Safety Standards (RSS-96) establish a maximum equivalent equilibrium volumetric activity (EEVA) of 200 Bq/m³ for existing buildings, corresponding to an effective dose of 11 mSv/year, and 100 Bq/m³ for new constructions (5.3 mSv/year). Protective measures are mandated for radon levels between 200–400 Bq/m³, while critical interventions are required above 400 Bq/m³, where doses exceed 21 mSv/year (**Table 1**). These thresholds are critical for assessing the radiological risks to Mailuu-Suu residents, particularly given the region's history of uranium mining and the proximity of residential areas to unsecured tailings sites. The standards align with international guidelines, such as those from the International Commission on Radiological Protection (ICRP), emphasizing the need for urgent action when radon levels exceed safe limits.

3.2. Radon Levels in Residential Buildings

The year-long radon-222 monitoring campaign (July 2001–July 2002) across 34 residential buildings in Mailuu-Suu city, Sary-Bee, and Yuzhny Karagach revealed alarmingly high concentrations, averaging 473.6 Bq/m³. This significantly exceeds the RSS-96 threshold of 200 Bq/m³ for existing buildings and the U.S. EPA's action level of 148 Bq/m³ as outlined in their radon mitigation guidelines [16]. In Mailuu-Suu city, 16 homes were tested, with 88% (14 homes) surpassing 200 Bq/m³, and 44% (7 homes) exceeding 400 Bq/m³, indicating a critical need for intervention. Sary-Bee village showed an average of 506.9 Bq/m³ across 12 homes, with 50% above 400 Bq/m³, while Yuzhny Karagach recorded the highest levels at 551.3 Bq/m³, with 83% of 6 homes exceeding 400 Bq/m³. Overall, 53% of all tested residences (18 homes) surpassed the critical 400 Bq/m³ threshold, highlighting widespread exposure risks. Seasonal variations showed higher radon levels in winter due to reduced ventilation, exacerbating exposure risks. These findings align with patterns observed in other uranium legacy sites, such as those in Central Asia, where proximity to tailings significantly elevates indoor radon concentrations as documented in studies of Kyrgyzstan's uranium mining legacies [17,18]. The radon monitoring campaign revealed elevated radon-222 concentrations across Mailuu-Suu, Sary-Bee, and Yuzhny Karagach (**Table 2**).

Table 1. Radiation safety standards in the Kyrgyz Republic (RSS-96).

Quantities	Values (Bq/m³)	Effective Dose (mSv/year)
New buildings: Sum (EEVARn + 4.6 EEVATn)	< 100	5.3
Existing buildings: EEVA of radon isotopes	≤ 200	11
Protective measures required	200–400	11–21
Critical intervention needed	> 400	> 21

Table 2. Radon levels in residential buildings in Mailuu-Suu and surrounding villages.

Location	Number of Houses	Average Radon Level (Bq/m³)	Houses > 400 Bq/m³	Houses 200–400 Bq/m³	Houses < 200 Bq/m³
Mailuu-Suu City	16	362.6	7 (44%)	7 (44%)	2 (12%)
Sary-Bee Village	12	506.9	6 (50%)	3 (25%)	3 (25%)
Yuzhny Karagach Village	6	551.3	5 (83%)	0 (0%)	1 (17%)
Total	34	473.6	18 (53%)		

3.3. Uranium Mill Tailings Characteristics

The 1.9 million cubic meters of uranium mill tailings in Mailuu-Suu, equivalent to approximately 3.04 million tonnes (assuming a density of 1.6 tonnes/m³), represent a substantial radiological burden. The total activity is estimated at 4.89 TBq, predominantly from radium-226 (3.80×10^{12} Bq), with contributions from uranium-238 (9.12×10^{11} Bq) and thorium-232 (**Table 3**). These radionuclides, part of the uranium-238 decay chain, release radon-222, a key contributor to health risks. The tailings' composition was derived from regional studies and validated against international data, such as those from the European Commission-TACIS project[13]. The high radium-226 content, with a specific activity of 3.66×10^{10} Bq/g, underscores its role as the primary source of radon emissions. The tailings' unsecured storage on tectonically unstable slopes increases the risk of environmental dispersion, particularly through windblown dust and leaching into the Mailuu-Suu River, affecting water quality and downstream ecosystems[4]. These characteristics are consistent with other Central Asian uranium legacy sites, where inadequate containment amplifies radiological hazards[18].

Table 3. Radiological characteristics of uranium mill tailings.

Radionuclide	Concentration (Bq/kg)	Specific Activity (Bq/g)	Total Activity (Bq)
Uranium-238	300	1.24×10^4	9.12×10^{11}
Radium-226	1250	3.66×10^{10}	3.80×10^{12}
Thorium-232	125	4.06×10^3	
Total			4.89×10^{12}

3.4. Health Impacts

Health surveys conducted in Mailuu-Suu revealed a significant disease burden linked to radiological exposure, particularly due to contamination of water resources from uranium mill tailings[19]. Medical records and clinical examinations of 70 women who recently gave birth in high-radiation zones showed elevated rates of lung, stomach, and kidney cancers, alongside respiratory diseases (e.g., chronic bronchitis, asthma), cardiovascular conditions, and congenital anomalies as documented in regional health impact assessments[20]. Pearson correlation coefficients indicated a strong positive association between radon exposure and lung cancer incidence ($r = 0.62$, $p < 0.01$), consistent with global studies identifying radon as the second leading cause of lung cancer[5]. Community surveys ($n = 150$) revealed widespread concern, with 78% of respondents expressing distrust in local institutions' ability to manage contamination, reflecting social and psychological impacts reported in local media[21,22]. A significant correlation was also found with congenital anomalies ($r = 0.58$, $p < 0.05$), particularly among children born in high-exposure areas. Placental analyses confirmed bioaccumulation of uranium and thorium isotopes, with correlations to increased placental weight ($r = 0.55$, $p < 0.05$) and congenital anomalies ($r = 0.60$, $p < 0.01$), aligning with findings on ionizing radiation effects[23]. Multivariate regression models, adjusting for confounders like age and smoking status, confirmed radon as a significant predictor of lung cancer ($\beta = 0.45$, $p < 0.01$).

Moreover, recent theoretical models in environmental toxicology highlight the cumulative and synergistic effects of chronic exposure to mixed contaminants, such as radionuclides combined with heavy metals observed in Mailuu-Suu's radioecological assessments[24]. These compound exposures, common in areas like Mailuu-Suu, may result in biological outcomes more severe than predicted by single-agent exposure models. This complexity underscores the need for comprehensive biomonitoring systems to assess multi-pathway exposures over time, as emphasized in studies of uranium waste stabilization[25]. Another study revealed that the incidence of certain gastrointestinal cancers was twice as high among individuals consuming water from the river compared to those who did not, likely due to contamination from uranium tailings leaching into water resources, as supported by hydrogeochemical monitoring data[19,26]. These health outcomes mirror findings from other uranium-affected regions, such as the Navajo Nation, where long-term exposure to radionuclides has led to similar disease patterns[27]. However, further investigation is necessary to draw definitive conclusions. One of the most concerning observations is the disproportionate cancer burden among women, who represent 70% of all cancer cases in the region. In Mailuu-

Suu, breast cancer ranks as the second most prevalent malignancy after lung cancer, with an average of 12 women diagnosed and 12 deaths recorded annually. Typhoid fever also constitutes a significant public health concern in Mailuu-Suu. While Kyrgyzstan typically reports approximately 50 typhoid cases annually, a localized outbreak in December 2013 affected nearly 100 individuals in a single village within the region. Subsequent testing of river water by scientists from the Institute of Medical Problems in December 2014 identified typhoid-causing bacteria. The presence of these pathogens during winter is atypical, as they are generally active only during warmer seasons. Researchers hypothesize that radioactive materials may be heating the river water, thus maintaining bacterial viability during colder months. Congenital anomalies represent an additional indicator of environmental radioactive exposure. A study conducted by the Institute of Medical Problems found that the prevalence of birth defects in Mailuu-Suu was three times higher than in Osh, the second-largest city in the country. The researchers correlated these anomalies with the proximity of parental residences to radioactive waste storage sites. According to the institute's findings, contaminated water is likely a contributing factor as further evidenced by hydrogeochemical monitoring [26]. These health outcomes mirror findings from other uranium-affected regions, such as the Navajo Nation, where long-term exposure to radionuclides has led to similar disease patterns [27].

This complexity underscores the need for more comprehensive biomonitoring systems that can assess multi-pathway exposures over time. Community resilience is also a critical factor often underrepresented in remediation literature. In Mailuu-Suu, the legacy of secrecy during the Soviet era has left a persistent void in risk communication. Empowering local stakeholders through transparent information dissemination and participatory decision-making can significantly improve the success of intervention programs. Studies from other post-Soviet uranium mining sites suggest that risk perception and trust in authorities are pivotal in public compliance with health advisories.

Lastly, there is a pressing need for educational initiatives that integrate environmental health literacy into school curricula and local healthcare training. Building local capacity to identify and respond to radiological hazards could transform passive victimization into proactive community engagement. Such grassroots empowerment aligns with the broader goals of sustainable development and environmental stewardship in post-industrial regions.

4. Discussion

The radiological legacy of Mailuu-Suu's uranium mining operations, spanning 1946 to 1968, has left a profound impact on the region's environment and public health. The 1.9 million cubic meters of uranium mill tailings, with a radiological activity of 4.89 TBq, represent a significant environmental hazard, as evidenced by elevated indoor radon-222 levels averaging 473.6 Bq/m^3 across 34 residences. These levels exceed Kyrgyzstan's RSS-96 standard of 200 Bq/m^3 and the U.S. EPA's action level of 74 Bq/m^3, underscoring the urgency of addressing this crisis. This discussion explores the multifaceted implications of these findings, structured into subsections to address radiological hazards, health impacts, socioeconomic challenges, mitigation strategies, and limitations, drawing on insights from the provided literature.

4.1. Radiological Hazards and Environmental Risks

The high radon-222 concentrations in Mailuu-Suu, particularly in Yuzhny Karagach (551.3 Bq/m^3, 83% of homes exceeding 400 Bq/m^3), are driven by the proximity of residential areas to unsecured tailings sites and the use of contaminated construction materials. The tailings, containing uranium-238, radium-226, and thorium-232, release radon-222, a decay product of radium-226, which accumulates in poorly ventilated homes [5]. The 1958 tailings dam failure, which released 600,000 cubic meters of radioactive waste into the Mailuu-Suu River, exemplifies the region's geological vulnerabilities, exacerbated by frequent seismic activity and landslides in the Fergana Valley [7]. This incident contaminated a vital water resource, affecting downstream communities in Kyrgyzstan and Uzbekistan, as noted in regional studies [4]. A study conducted by the Institute of Nuclear Physics of the Academy of Sciences of Uzbekistan found that radioactive contamination levels in the river during spring were twice as high as in summer, due to heavy rainfall washing radioactive waste from tailings ponds and landfills.

It highlights similar concerns, emphasizing the tailings' instability and the transboundary nature of river contamination, which amplifies ecological damage and threatens water security for agriculture and drinking [4]. The leaching of radionuclides and heavy metals, such as lead and zinc, into the Mailuu-Suu River further disrupts biodiversity and undermines livelihoods dependent on fisheries and irrigation [8]. Comparisons with other uranium legacy sites, such as the Navajo Nation and Arlit, Niger, reveal parallel challenges, including windblown dust dispersion and groundwater contamination. However, Mailuu-Suu's tectonic instability adds a unique risk of catastrophic tailings failure [27,28]. The environmental burden of tailings underscores the need for robust containment to prevent further dispersion, aligning with IAEA safety standards [18]. These findings highlight the critical interplay between geological instability, radiological contamination, and environmental degradation in Mailuu-Suu.

4.2. Health Impacts and Vulnerable Populations

The health surveys conducted in Mailuu-Suu reveal a significant disease burden linked to radiological exposure, with elevated rates of lung, stomach, and kidney cancers, respiratory diseases, and congenital anomalies. The strong correlation between radon exposure and lung cancer ($r = 0.62$, $p < 0.01$) aligns with global evidence identifying radon-222 as the second leading cause of lung cancer, particularly in environments with inadequate ventilation [5]. The discussion of health risks similarly emphasizes radon's carcinogenic potential, noting its impact on vulnerable populations [5]. The correlation with congenital anomalies ($r = 0.58$, $p < 0.05$) and placental bioaccumulation of uranium and thorium ($r = 0.60$, $p < 0.01$) underscores the risks to pregnant women and children, who are particularly susceptible due to developing physiological systems. Placental analyses showing increased weight ($r = 0.55$, $p < 0.05$) suggest that radionuclide exposure may disrupt fetal development, consistent with findings from post-Chernobyl studies [23]. The elderly also face heightened risks, with elevated rates of respiratory and gastrointestinal disorders linked to chronic exposure to heavy metals like lead, as noted in regional assessments [4]. This research focuses on vulnerable groups, reinforcing these concerns, highlighting the need for targeted health interventions. Multivariate regression models, adjusting for confounders like age and smoking, confirm radon's role as a significant predictor of lung cancer ($\beta = 0.45$, $p < 0.01$), providing robust evidence of causality. These health impacts mirror those observed in other uranium-affected regions, such as the Navajo Nation, where long-term exposure to radionuclides has led to similar disease patterns. However, Mailuu-Suu's limited healthcare infrastructure exacerbates outcomes [27]. The transboundary implications of water contamination further amplify health risks, as downstream communities face exposure through contaminated drinking water and agricultural products [4].

4.3. Socioeconomic and Community Challenges

The community survey ($n = 150$) revealed widespread distrust, with 78% of respondents expressing skepticism about local institutions' ability to manage radiological contamination. This distrust reflects a broader social challenge in post-Soviet uranium legacy sites, where historical mismanagement and lack of transparency have eroded public confidence [29]. Community-driven remediation efforts, such as those using uranium sorption techniques, can reduce environmental contamination and protect agricultural livelihoods, addressing socioeconomic concerns [30]. Detailed assessments of radionuclide content in Mailuu-Suu tailings highlight the need for community education to mitigate distrust and inform residents about exposure risks [31]. International support, such as from the European Bank for Reconstruction and Development, has been crucial in funding remediation efforts that stabilize local economies and reduce environmental risks [32]. Environmental challenges in tailings remediation, such as unsecured waste sites, further exacerbate community distrust, necessitating transparent communication [33]. The socioeconomic dependence on mining in Mailuu-Suu, as highlighted in regional studies, complicates remediation efforts, as communities fear economic disruption from tailings stabilization or relocation [8]. Radiological assessments underscore the importance of regulating construction materials to mitigate health risks, thereby reducing the economic burden of radiation-related illnesses [34]. Stricter waste management policies can ensure safer environments for agriculture, supporting socioeconomic stability by protecting livelihoods dependent on the Mailuu-Suu River [35]. The economic constraints underscore the high healthcare costs associated with radiation-related illnesses, which strain local budgets and limit access to specialized care [4]. This socioeconomic burden is compounded by the region's reliance on the contaminated Mailuu-Suu River for agriculture, which sustains livelihoods but poses ongoing exposure risks. Community engagement, as emphasized in this research, is critical to rebuilding trust and ensuring the success of mitigation efforts. Experiences from other uranium legacy sites, such as Arlit, Niger, show that transparent communication and participatory decision-making can enhance community support for remediation [28]. In Mailuu-Suu, addressing these socioeconomic challenges requires integrating public health strategies with economic diversification, such as promoting alternative industries like renewable energy, as suggested in the literature [36] such as promoting alternative industries like renewable energy to foster long-term economic resilience, as demonstrated in remediation progress studies [36].

4.4. Mitigation and Remediation Strategies

Effective mitigation of Mailuu-Suu's radiological hazards requires a multifaceted approach, as outlined in WHO and IAEA guidelines [5,18]. Indoor radon mitigation, including ventilation improvements and sealing entry points, is critical to reducing exposure, particularly in high-risk areas like Yuzhny Karagach. It emphasizes structural interventions with these recommendations, advocating for soil decompression techniques and regulations on construction materials [5,6]. Tailings remediation, such as stabilizing dams with engineered barriers and leveraging uranium sorption techniques to minimize radionuclide dispersion [30], is essential to prevent environmental dispersion, as supported by IAEA frameworks [18]. The European Bank for Reconstruction and Development has provided significant funding for such remediation efforts, emphasizing the relocation of high-risk tailings to secure sites [32]. It highlights similar strategies, noting the importance of dust control to minimize windblown contamination [33]. Regulations on construction materials, informed by radiological assessments, are also critical to reducing exposure risks [34]. Water purification programs are needed to address river contamination, ensuring safe drinking water and agricultural inputs [4]. Stricter waste disposal and water treatment regulations, as recommended in environmental performance reviews, are essential to support these efforts [35]. Community-driven initiatives, informed by local perceptions, can enhance the effectiveness of these measures, as evidenced by successful remediation projects in Central Asia [32]. The call for global cooperation is particularly relevant, given Kyrgyzstan's limited resources. International support from organizations like the European Bank for Reconstruction and Development (EBRD) and the World Bank has been instrumental in funding remediation efforts, but sustained investment is needed [28,32]. Public health interventions, including specialized medical centers and screening programs for vulnerable groups, are critical to address the disease burden, as emphasized in the manuscript [20]. Awareness campaigns, as recommended by the U.S. EPA, can educate residents about radon risks and mitigation techniques [16].

4.5. Limitations and Future Directions

The reliance on 2001–2002 data is a primary limitation, as remediation efforts may have altered current conditions, though recent reports confirm persistent contamination [18,32]. The small sample size of health surveys (e.g., 70 women) limits generalizability, necessitating larger cohort studies to validate findings. It acknowledges limitations, noting the need for updated data to assess ongoing risks. The absence of real-time monitoring systems hinders timely interventions, a challenge also highlighted in the call for enhanced environmental monitoring through advanced radionuclide content assessments [30,31]. Future research should prioritize longitudinal studies to track health outcomes, real-time radon and water quality monitoring, and socioeconomic analyses to evaluate the impact of remediation on local communities. Integrating advanced technologies, such as remote sensing and GIS, can improve the mapping of radiological hotspots, as demonstrated in other uranium legacy sites [31]. International collaboration, guided by IAEA and WHO frameworks, is essential to provide technical expertise and funding, ensuring sustainable remediation and public health improvements [18]. It emphasizes long-term resilience through infrastructure stabilization and community health programs as a roadmap for these efforts, highlighting the need for a multidisciplinary approach to address Mailuu-Suu's complex challenges.

Addressing the radiological legacy of Mailuu-Suu requires a multidisciplinary approach that encompasses advanced monitoring technologies, robust environmental remediation efforts, comprehensive public health campaigns, and international collaboration. Investments in real-time radiological monitoring systems, such as automated radon detectors, could enhance the ability to track exposure levels and identify high-risk areas[18]. Remediation efforts should prioritize the stabilization of tailings dams to prevent future breaches, particularly given the region's geological vulnerabilities[7]. Public health campaigns, successful in Western initiatives, should focus on educating residents about radon risks and promoting simple mitigation techniques, such as improving home ventilation[16]. International partnerships, potentially involving organizations like the International Atomic Energy Agency, could provide technical expertise and funding to support these efforts[28]. By integrating these strategies, it is possible to mitigate the enduring impacts of Mailuu-Suu's uranium mining legacy, protect the health of its residents, and promote sustainable environmental stewardship for future generations.

5. Conclusion

The radiological legacy of uranium mining in Mailuu-Suu poses a severe threat to public health and environmental integrity. This study highlights that 53% of sampled residences exceed 400 Bq/m^3, with 88% in Mailuu-Suu city surpassing the 200 Bq/m^3 RSS-96 threshold, driven by proximity to tailings, contaminated construction materials, and poor ventilation. Significant correlations between radon exposure and health outcomes, including lung cancer ($r = 0.62$, $p < 0.01$) and congenital anomalies ($r = 0.58$, $p < 0.05$), underscore the crisis's severity. Community distrust (78% of survey respondents) further complicates mitigation efforts. Despite Kyrgyzstan's efforts, limited resources and outdated infrastructure hinder progress. International collaboration, guided by the WHO and IAEA frameworks, is critical for implementing advanced monitoring, tailings remediation, and public health interventions. Despite recent initiatives aimed at addressing environmental pollution in Kyrgyzstan, significant systemic challenges impede progress toward sustainable remediation. The nation's radiological monitoring infrastructure remains critically under-resourced, characterized by outdated technology and a paucity of trained personnel, which limits the scope and accuracy of environmental assessments. Moreover, public awareness of the health risks associated with radon exposure remains markedly deficient, in stark contrast to the robust educational campaigns implemented in many developed nations. This knowledge gap perpetuates behaviors that exacerbate exposure, such as the continued use of contaminated building materials and insufficient adoption of radon mitigation strategies, such as enhanced ventilation or sealing of building foundations. The environmental legacy of uranium mining in Mailuu-Suu, compounded by historical incidents such as tailings dam failures, underscores the urgent need for comprehensive remediation efforts to prevent further ecological degradation and mitigate downstream contamination of vital water resources.

While Kyrgyzstan has demonstrated a commendable commitment to environmental restoration, the scale and complexity of the radiological legacy in Mailuu-Suu necessitate enhanced international collaboration and resource allocation. Comparative analyses with other uranium legacy sites, such as those in Central Asia and beyond, reveal similar challenges, including persistent environmental contamination and elevated disease burdens. However, Mailuu-Suu's constrained economic and technical capacity highlights the critical role of global partnerships in facilitating effective mitigation strategies. The World Health Organization's guidelines for radon management, which emphasize structural interventions and community education, offer a viable framework for addressing indoor radon exposure. Additionally, addressing the socioeconomic dimensions of this crisis, including the healthcare costs associated with radiation-related illnesses and the region's economic dependence on mining, is essential for fostering long-term resilience and sustainable development. Collectively, these findings emphasize the imperative for a multidisciplinary approach that integrates advanced monitoring, robust mitigation measures, and comprehensive public health interventions to address the enduring radiological challenges in Mailuu-Suu.

6. Recommendations

- Enhanced Environmental Monitoring:
  - Deploy real-time radon monitoring networks[30].
  - Conduct regular water, soil, and air quality assessments[31].
  - Equip monitoring services with advanced tools and training[25].
- Tailings Remediation:
  - Stabilize tailings dams with engineered barriers[19].

    - Relocate high-risk tailings to secure sites [32].
    - Implement dust control measures [33].
- Radon Mitigation in Buildings:
    - Use soil decompression techniques and seal entry points [5,6].
    - Enforce regulations on construction materials [34].
- Public Health Interventions:
    - Establish specialized medical centers for radiation-related illnesses [21].
    - Implement screening programs for vulnerable populations [20].
    - Launch awareness campaigns on radon risks [16].
- Policy and Infrastructure Development:
    - Enforce stricter waste disposal and water treatment regulations [35].
    - Invest in alternative energy sources [36].
    - Develop water purification programs [4].
- Community Support:
    - Consider relocating high-risk residents with consent and compensation [37].
    - Provide socioeconomic support and job training [29].

Author Contributions

Conceptualization, A.D.E. and K.D.K.; methodology, A.D.E.; software, K.D.K.; validation, A.D.E. and K.D.K.; formal analysis, K.D.K.; investigation, A.D.E.; resources, K.D.K.; data curation, K.D.K.; writing—original draft preparation, A.D.E.; writing—review and editing, K.D.K.; visualization, K.D.K.; supervision, A.D.E.; project administration, A.D.E.; funding acquisition, K.D.K. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data supporting the reported results, including radon monitoring data from July 2001–July 2002 and health survey data, are available upon request from the corresponding author, A.D. Egemberdieva. No publicly archived datasets were generated or analyzed during this study.

Conflicts of Interest

The authors declare no conflict of interest.

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