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Safety Assessment of TENORM Waste Landfill on Bangka Island Using Resrad Offsite 4.0

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ABSTRACT

Bangka Island faced serious environmental challenges due to TENORM (Technologically Enhanced Naturally Occurring Radioactive Materials) waste from tin mining activities. The waste contained radionuclides such as U-238, Th-232, and K-40, which could have had detrimental effects on human health and the environment. To solve this problem, TENORM waste should be disposed of in the class II landfill facility. The Class II landfill was more efficient by cost than the Class I landfill. The landfill design provide a waste contamination layer with dimensions of 160 × 160 × 3 meters. This landfill class has 5 layers from top to bottom cover layers such as the contamination or waste layer, protective coating layer, layer for collecting and transferring, geomembrane layer, soil barrier layer, leak detection system layer, and base layer, which each layer was intended to safeguard against contamination. These protective layers were required to adhere to precise specifications regarding material, thickness, and hydraulic conductivity to effectively manage waste and leachate. Additionally, the base layer consisted of compacted clay, designed to regulate hydraulic conductivity and offer sustained environmental protection. This paper will discuss the radiological safety assessment of this landfill design. This design was modeled using Resrad Offsite 4.0 software to assess its radiation safety in order to fulfill landfill safety requirements. The simulation results showed a maximum radiation dose of 0.40537 mSv per year at a distance of 200 meters from the landfill center, which was estimated to persist for 29,265 years after the landfill was closed. The cancer risk probability was estimated to be 4.25×10^{-4}. More importantly, this dose was still below the safe limit set by BAPETEN (Nuclear Energy Regulatory Agency) for public radiation exposure, which is 1 mSv per year. The class II landfill design, based on the simulation results, was safe for public health and the environment.

INTRODUCTION

Bangka Island is known for its tin industries besides white pepper and fish crackers [1]. The tin-bearing rock stretches from South China, Myanmar, Thailand, and West Malaysia to Indonesia. This line is called the South Asian Tin Belt Zone [2]. In Indonesia, the tin belt extends from the Karimun Islands, Singkep Islands, and Bangka Belitung Islands to West Kalimantan [3]. Tin exploration is not only conducted on land but also at sea to obtain the best tin ore.

It must go through many processes to produce pure tin from natural sources. The process is divided into two steps: the exploration process to find tin locations and the exploitation process to obtain and extract tin from nature. These steps begin with collecting tin ore from the soil, river, and sea, which is then processed to obtain tin through washing, separation, processing, smelting, and refining [4].

The natural tin ore contains many other valuable minerals besides tin, such as monazite, zircon, ilmenite, and xenotime [5]. These minerals contain radioactive elements such as Thorium-232 and Uranium-238 isotopes and their progeny.

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As a concern, Uranium-238 and Thorium-232 have a long half-life and potentially harm humans and the environment if improperly handled. The radioactive elements that form naturally are called NORM (Naturally Occurring Radioactive Materials). If the radioactive concentration increases due to human activities, including mining and processing of tin ore, it is called TENORM (Technologically Enhanced Naturally Occurring Radioactive Materials) [6]. The tin industry is among the sectors that produce TENORM, so it is necessary to pay attention to radiation safety issues for workers, society, and the environment [7].

Effective TENORM regulations help control exposure to radioactive materials in various industries, aligning with broader radiation protection principles. In Indonesia, TENORM supervision has been regulated by Government Regulation (PP) number 45 of 2023 regarding ionizing radiation safety and security, as well as radioactive sources [8] and Head of BAPETEN Regulation number 9 of 2009 regarding intervention to radiation from TENORM [9].

Workers at mining sites and tin processing factories are potentially exposed to minerals that contain NORM and radioactive waste exceeding the dose limit of 20 mSv/year, whereas the society around mining sites and tin processing factories have a dose limit of 1 mSv/year. Based on those concerns, workers and communities near the site should be included in a thorough radiation protection program that meets basic safety standards requirements [10]. Radiation protection considerations include the principles of as low as reasonably achievable (ALARA) and the principles of JOD (justification, optimization, and dose limitation). Many tin tailings storage and waste are poorly managed in West Bangka Regency. This situation can lead to public exposure outside the site, especially with medium rainfall precipitation, where water can carry radioactive elements outside the site [11]. The solution to eliminate or at least minimize the environmental risk posed by radiological hazards and society is to construct a landfill facility and dispose of TENORM waste [12]. The doses humans receive will be related to cancer risk and other diseases.

The problem with TENORM waste, which can no longer be processed and still contains highly radioactive substances, is whether it will continue to be placed in the work area or disposed of according to existing regulations. If it is to be stockpiled somewhere, the best place for the landfill, who will build it, and how safe it will be after the closure of the landfill must be determined. This problem must be resolved in Bangka Island, particularly in Indonesia. In addition, the problem in Bangka Belitung, as well as in Indonesia, is the uncertainty of TENORM waste inventory data, so Indonesia does not know with certainty the amount of TENORM waste and the amount of waste generated per year, resulting in ineffective and incomprehensive handling. This inventory data includes at least the volume of waste and the radioactivity level of the TENORM waste.

Tin ore contains high natural radionuclides, while mine tailings have lower levels. To concentrate tin, the shaking table method is used, producing tin ore with around 70 % concentration for smelting. The process also produces tin tailings rich in radionuclides, which are processed to create by-products like zircon, monazite, and ilmenite. The smelting process yields pure tin, while the final slag has high radionuclide levels. The main waste issue lies in the final slag. Before the by-product industry, tin sand tailings were discarded, causing environmental harm. With the industry, this problem is addressed, and the final slag is managed through a landfill [13].

TENORM waste management from upstream to downstream in Indonesia needs to be done in an integrated manner. Landfill facilities can be used for various types of waste. The higher the hazard level of the waste to be placed, the higher the quality or safety level of the landfill that will be applied [14]. TENORM landfill facilities are developed to contain the waste and avoid radiation exposure to humans and the surroundings. The purpose of selecting a landfill site is to ensure radiation protection and comply with relevant laws and regulations. This research refers to several standards issued by the Internasional Atomic Energi Agency (IAEA) and existing international recommendations and guidelines [15].

The smelting procedure that produces TENORM refuse is designated as second-category perilous waste emanating from specific origins. Ordinance of The 63rd Regulations of the Minister of Environmental and Forestry Affairs from 2016 contains regulations for storage facilities for this waste [16]. In terms of radioactivity, tin slag is classified as a waste of very low levels, which necessitates appropriate repository solutions, such as a landfill. TENORM waste having a concentration of activity exceeding 1 Bq/gram (from a series of Uranium and Thorium) is advised to be placed in class I or class II landfills. Class I and class II landfills have similar capacities to accommodate leachate after the facility is closed [17].

References illustrating the use of RESRAD in a comparable research context have been included. The closest study is Anggraini et al. (2021), which showed the application of RESRAD in a class III landfill of tin tenorm waste [18]. The novelty of this study is the use of a class II landfill design, which is in accordance with the regulations of the Minister of Environmental and Forestry Affairs.

The study aims to determine the potential radiation dose that can be received by the surrounding community due to the construction of the TENORM industrial waste disposal site for class II tin on Bangka Island. Besides radiological dose, this study also estimates the cancer risk probability that will affect the society around the landfill facility. The study's results offer recommendations to all stakeholders in the tin industry to guarantee that safety is prioritized to prevent radiological risks to humans and the environment [19].

This study outlines modeling techniques and parameters for estimating the concentration of ambient air and beneath-surface water, as well as outer dose rates. The sources included in the inventory are estimated and modeled based on the amount of TENORM material released into the environment over time. In this paper, storage depends on the amount of waste, the layers of the landfill building, and the surrounding environment.

In developing a TENORM waste landfill facility for the tin industry, it is necessary to carry out three stages of the process before the start of construction: Determination of site criteria and preparation of landfill designs based on government regulations and IAEA safety standard requirements and expert recommendations; Collection and confirmation of site data, technological sustainability, and feasibility; Evaluation of information and data collection for safety assessment.

The research area only covers the West Bangka Regency area. Site criteria assessment has been carried out based on the IAEA methodology in IAEA Safety Standard SSG-60. Based on these results and the addition of waste characteristic data, a landfill design was made. The next stage is conducting data analysis adopting methods, standards, and operational systems based on the latest best practical experience from other countries by regulations related to TENORM landfill. The landfill should be designed by incorporating several engineered barriers to minimize environmental release levels, especially groundwater. Water is an essential element for life on Earth, as it is one of the most precious commodities. The quality and abundance of water are crucial for human existence [20]. The design process must align with the need to guard the environment and public health. The primary design elements include the landfill subbase, coating, leachate handling system, gas monitoring system, rainwater management, and top cover [21].

The government's efforts in regulating and supervising ensure the protection of the community and environment by making several regulations related to TENORM waste monitoring. The top two regulations are Indonesian Act No. 10, 1997, concerning Nuclear Energy, and Act No. 32, 2009, concerning environmental safeguarding and oversight [22,23]. In detail, a derivative regulation of the law is prepared, namely government regulations. Government Regulation No. 101 of 2014 regulates risky waste handling [24]. TENORM waste is regulated as dangerous waste from specific sources: category II, defined by a radioactive contamination level of 1 Bq/cm² or higher, along with specific activity concentrations (see [16]), namely 1 Bq/gram for member radionuclide the Series of Uranium and Thorium; or 10 Bq/gram for Potassium.

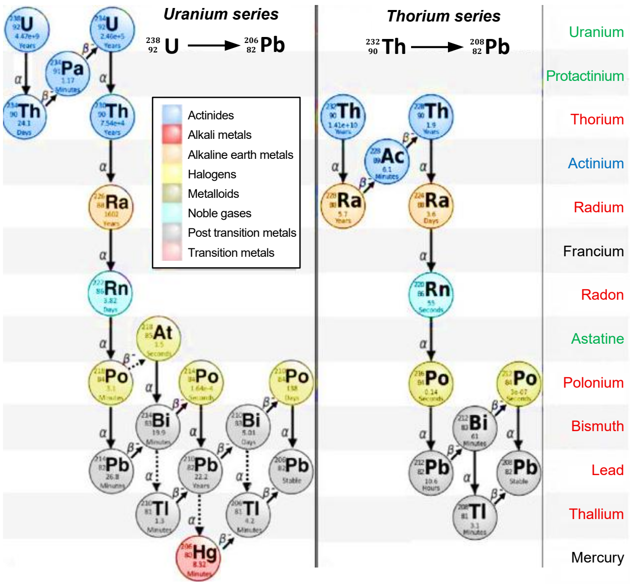

Fig 1. Probable decay scheme of radionuclides produced from TENORM [25].

Figure 1 shows the probable decay scheme of radionuclides produced from TENORM, such as U-238, Th-232, Ra-226, and K-40, each undergoing unique decay processes. U-238 transforms through a sequence of alpha and beta emissions, eventually stabilizing as Pb-206. Ra-226, a daughter of U-238 decay, emits alpha radiation to become Rn-222, which then decays further into Po-218 and Bi-214. Th-232 follows a similar decay trajectory, producing Ra-220 and other intermediate elements, ultimately stabilizing as Pb-208. K-40, a naturally present isotope, decays via beta radiation into stable Ar-40. Throughout these decay chains, alpha particles, beta particles, and gamma rays are emitted, with radon gas and its decay products, such as Pb-210, posing serious health hazards when inhaled or ingested [25]. The radiation released by these isotopes can lead to severe health problems like lung cancer, bone damage, and other conditions. Thus, effective containment and management of TENORM are vital, especially in industries such as mining, oil extraction, and water treatment, to reduce the risk of radiation exposure.

As referred to in the member Uranium and Thorium series, radionuclides include U-238, Pb-210, Ra-226, Ra-228, Th-228, Th-230, Th-234, and Po-210. Nevertheless, Po-210 only applies to the determination of the concentration of the activity of radionuclides from a series of Uranium and Thorium in hazardous waste stemming from natural gas extraction activities and mining processing. If the radioactivity level is below the limit of the criteria above, the prohibition to use hazardous waste will be excluded.

Requirements and procedures for landfilling are also governed by the year 2016 regulation no. 63 of the Minister of Environment and Forestry [16]. Based on this regulation, there are three landfill types for hazardous waste classes. A significant difference between these classes is found using geomembrane layers [26]. Therefore, TENORM waste should be disposed of in class I or 2 landfills. For cost efficiency, it uses landfill class II, which is cheap to build but obeys the regulations.

Table 1 shows comparison features among class I, class II, and class III landfills. By observing Table 1, the differences among class I, class II, and class III landfills can be distinguished. The landfill's criteria for TENORM waste are at least: (a) Dump layer (TENORM and/or other hazardous materials); (b) Base and liner structure; (c) Capping systems; (d) Leachate and gas control system; (e) Safety and security monitoring system.

Table 1. Difference among landfill class types [26].

Class I	Class II	Class III
Cover Layer	Cover Layer	Cover Layer
Contamination Layer (Waste)	Contamination Layer (Waste)	Contamination Layer (Waste)
Protection layer when operation	Protection layer when operation	Protection layer when operation
Leachate Collection and Transfer System	Leachate Collection and Transfer System	Leachate Collection and Transfer System I
Geomembrane layer I	Geomembrane layer	Soil barrier layer
Soil barrier layer	Soil barrier layer	Leachate Collection and Transfer System II
Leak detection system layer	Leak detection system layer	Base layer
Geomembrane layer II	Base layer	
Base layer		

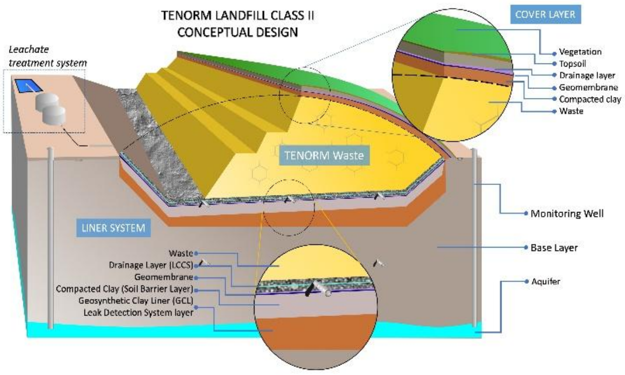

Fig 2. Design of class II landfill facility [26].

Based on Fig. 2, the design was used to consider the safety aspect and the cost of construction. In our opinion, a class II landfill is more appropriate for this TENORM waste than other classes, which already meet safety standards by regulations but with cheaper construction costs than a class I landfill, so it is more efficient [26].

From the enrichment process, it produces about 70 % of high-grade tin and tin tailings [27]. The tailings are by-products, including monazite, ilmenite, zircon, and xenotime, which possess an intense presence of radionuclides and are economically valuable [28]. Furthermore, the final tin residue exhibits a higher radioactive substance concentration, including Ra-226, Th-232, and K-40, but does not have economic value to process. So that the final slag will be sent to the landfill. The last tin slag-based field data consists of radioactive isotopes such as Ra-226 = 4.744 Bq/g; Th-232 =16.431 Bq/g; and K-40 = 0.527 Bq/g [13].

METHODOLOGY

Study area

The study was carried out in the West Bangka Regency, Bangka Island, Indonesia, a region recognized for its tin processing activities (Fig. 3). This location was chosen because of its closeness to tin processing centers and the presence of clay-rich layers in the Tanjung Genting Formation, which serve as a natural barrier against the leaching of radionuclides. The selected landfill site, which is located in the Terentang Sub-District of Kelapa District, provided favorable geological and environmental conditions for the secure management of TENORM waste [13].

Fig 3. Map of Bangka Island with proposed site (marked by red spot) at Terentang Sub District, Kelapa District, West Bangka Regency [13].

Landfill design

The landfill cover layer encompasses vegetation, topsoil, and compressed clay, acting as a bulwark to attenuate exposure, avert aqueous infiltration, regulate gas emissions, and bolster plant growth. The protector layer must be no less than 30 cm thick, devoid of printed materials, and exhibit pollutant concentrations beneath prescribed thresholds. It is fashioned to thwart damage to the sublayer during refuse deposition and is affixed to both the foundation and cell walls. The Leachate Collection and Transfer System (LCTS) layer demands a minimum of 30 cm of granular soil with reduced hydraulic conductivity. A soil barrier, either compacted clay or Geosynthetic Clay Liner (GCL), must conform to particular hydraulic conductivity norms. The geomembrane layer, composed of HDPE, is engineered to endure stresses across the landfill's tenure. The base layer, a compressed clay matrix, requires a minimum thickness of 1 meter with a designated hydraulic conductivity range. Cross section of class II landfill is depicted in Fig. 4.

The leakage detection layer (Geonet HDPE) was negligible for this study because limitation of RESRAD Offsite software, which has a maximum of 5 layers, and this layer has the smallest impact on the landfill.

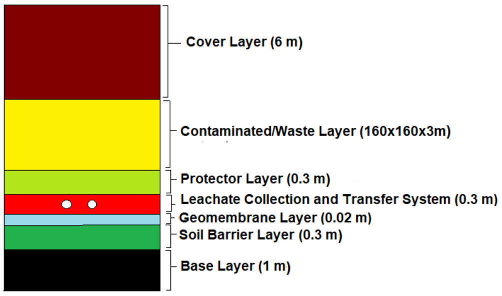

Fig 4. Cross section of class II landfill, simulated in this paper.

Modeling approach

The study utilized RESRAD Offsite 4.0 software to simulate radiological dose exposures and assess potential cancer risks for populations near contaminated sites. The software evaluated exposure pathways such as atmospheric dispersion, groundwater transport, and direct contact. Input parameters included site-specific data, like the dimensions and thickness of the contaminated area, as well as default values where local data were unavailable. Environmental factors such as hydraulic conductivity, porosity, and evapotranspiration were incorporated for model accuracy [29]. How radioisotopes accumulate in the food chain is a crucial aspect of risk assessment, including inhalation, ingestion, and external radiation, all of which were modeled [30]. This study focuses on human activities within a 200-meter radius of the landfill center.

Data input parameter

The dose assessment method is to create a simulation in the RESRAD software. The input data was obtained from our previous research, reference papers, Statistics Agency books, and the software's default data as tabulated in Table 2. The more recent and the closer the data is taken for Resrad input, the more accurate the results will be.

Table 2 Parameters for resrad input.

Parameter	Unit	Value	Source
Area of the contaminated zone	m^2	8,093	[13]
Activity of Th-232	Bq/g	16.431	[13]
Activity of Ra-226	Bq/g	4.744	[13]
Activity of K-40	Bq/g	0.527	[13]
Dimension of Area Contamination	m	160 × 160	Scenario Asumsion
Thickness of contaminated zone	m	3	Scenario Asumsion
Length parallel to aquifer flow	m	150	Scenario Asumsion
Dry bulk/Density of contaminated zone	g/cm^3	2.00	[13]
Contaminated zone erosion rate	m/y	0.001	[31]
Contaminated zone total porosity	-	0.43	[31]
Contaminated zone effective porosity	-	0.33	[31]
Contaminated zone hydraulic conductivity	m/y	100	[31]
Contaminated zone b parameter	-	4.05	[31]
Contaminated zone field capacity	-	0.1	[31]
Contaminated zone runoff coefficient	-	0.1	[31]
Evapotranspiration coefficient	-	0.42	[32]
Precipitation	m/y	2.073	[33]
Irrigation	m/y	0.2	Resrad Default
Well pumping rate	m^3/y	5,100	Resrad Default
Number of unsaturated zone strata	-	6	[16]

Parameter	Unit	Value	Source
Basic Layer			
Unsaturated zone 1 thickness	M	1	[16]
Unsaturated zone 1 dry bulk/density	g/cm^3	1.2	[31]
Unsaturated zone 1 total porosity	-	0.42	[31]
Unsaturated zone 1 effective porosity	-	0.2	[31]
Unsaturated zone 1 b parameter	-	11.4	[31]
Unsaturated zone 1 field capacity	-	0.45	[31]
Unsaturated zone 1 hydraulic conductivity	m/y	40.5	[31]
Leakage Detection Layer (Geonet HDPE)	* Negligible for Resrad simulation because maximum 5 layers and this layer has the smallest impact on landfill		
Leakage Detection Layer thickness	m	0.01	[16]
Leakage Detection Layer dry bulk/density	g/cm^3	0.94	[31]
Soil Barrier Layer			
Unsaturated zone 2 thickness	m	0.3	[16]
Unsaturated zone 2 dry bulk/density	g/cm^3	1.2	[31]
Unsaturated zone 2 total porosity	-	0.42	[31]
Unsaturated zone 2 effective porosity	-	0.2	[31]
Unsaturated zone 2 b parameter	-	11.4	[31]
Unsaturated zone 2 field capacity	-	0.45	[31]
Unsaturated zone 2 hydraulic conductivity	m/y	40.5	[31]
Geomembrane Layer			
Unsaturated zone 3 thickness	m	0.02	[16]
Unsaturated zone 3 dry bulk/density	g/cm^3	1.7	[34]
Unsaturated zone 3 total porosity	-	0.427	[34]
Unsaturated zone 3 effective porosity	-	0.2	[34]
Unsaturated zone 3 b parameter	-	5.3	Resrad Default
Unsaturated zone 3 field capacity	-	0.367	[34]
Unsaturated zone 3 hydraulic conductivity	m/y	315	[34]
Leachate Collection and Transfer System			
Unsaturated zone 4 thickness	m	0.3	[16]
Unsaturated zone 4 dry bulk/density	g/cm^3	3	[31]
Unsaturated zone 4 total porosity	-	0.34	[31]
Unsaturated zone 4 effective porosity	-	0.28	[31]
Unsaturated zone 4 b parameter	-	4.05	[31]
Unsaturated zone 4 field capacity	-	0.89	[31]
Unsaturated zone 4 hydraulic conductivity	m/y	10,000	[31]
Protector Layer			
Unsaturated zone 5 thickness	m	0.3	[16]
Unsaturated zone 5 dry bulk/density	g/cm^3	1.44	[31]
Unsaturated zone 5 total porosity	-	0.45	[31]
Unsaturated zone 5 effective porosity	-	0.2	[31]
Unsaturated zone 5 b parameter	-	4.38	[31]
Unsaturated zone 5 field capacity	-	0.1	[31]
Unsaturated zone 5 hydraulic conductivity	m/y	4,930	[31]
Saturated Zone Thickness	m	150	Scenario Assumption
Inhalation rate	m^3/y	8,400	Resrad Default
Cover Layer			
Cover zone thickness	m	6	Scenario Assumption
Cover zone dry bulk density	g/cm^3	1.2	[31]
Cover zone total porosity	-	0.47	[31]
Mass loading for inhalation	g/m^3	1×10^{-4}	Resrad Default
Soil ingestion rate	g/y	36.5	Resrad Default
Drinking water intake	L/y	730	[33]
Fruit. Vegetable. and grain consumption	kg/y	9.54	[33]
Leafy vegetable consumption	kg/y	17.1	[33]
Milk consumption	L/y	12.64	[33]
Meat consumption	kg/y	5.46	[33]
Fish consumption	kg/y	10.37	[33]
Crustacea and Mollusca	kg/y	4.44	[33]

Simulation process

The simulation process involved several stages, beginning with the integration of input data into the RESRAD Offsite 4.0 software. Site-specific factors, such as the presence of clay barriers and geomembrane layers, were incorporated into the landfill design. The software was then used to simulate radiological doses over up to 10,000 years. The simulation produced outputs that included dose estimates for nearby populations and projected excess cancer risks at various intervals. Once the simulation was complete, the results were analyzed to identify trends and evaluate the safety of the landfill design. Graphs were generated to visualize dose patterns over time and highlight the contributions of specific radionuclides, such as K-40, Ra-226, and Th-232.

The simulation results were thoroughly analyzed to evaluate the safety and effectiveness of the landfill design. Maximum dose levels were compared with safety thresholds to confirm compliance. The integrity of the landfill system and its engineered barriers was also assessed to ensure long-term environmental protection. Furthermore, excess cancer risks were estimated based on the effective doses over time, and these results were compared with acceptable risk thresholds to assess the potential public health impacts [14].

To get an estimation of the dose received by the society around the site and the excess risk of cancer that may arise due to radiation, it can be formulated using Eqs. (1-3) as follows [29]:

$$(Dose)_p\,(t) = DCF_{j,p}\,(_t) \times ETF_{j,p}(_t) \times SF_{i,j}\,(_t) \times S_i(o)) \qquad (1)$$

Where:

$(Dose)_{j,p}(t)$ = Effective dose (mrem/year),

$DCF_{j,p}(t)$ = Factor of dose adjustment (mrem/pCi)

$ETF_{j,p}(t)$ = Factor of the environmental dispersion (g/year)

$SF_{i,j}(t)$ = Source factor

$S_i(0)$ = Soil concentration of radionuclides

$$(Excess\ Cancer\ Risk)_{j,p}(t) = (Intake)_{j,p}(t) \times Sf_{j,p} \times ED \qquad (2)$$

$$(Excess\ Cancer\ Risk)_{j,p}(t) = \sum_{t=1}^{M} ETF_{J,P}(\mathrm{t}) \times SF_{i,j}(\mathrm{t}) \times S_i(0) \times Sf_{j,p} \times \mathrm{ED} \qquad (3)$$

Where:

$(\text{Intake})_{j,p}$ = Pathways of ingestion and inhalation.
M = Number of radionuclides that were initially present
$SF_{i,j}(t)$ = Slope Factor Radionuclides
ED = Expose Duration (year).

In the current investigation, the input data is obtained from the results of our previous research (secondary data), reference data from other papers and books, and default values from the RESRAD software, where the data was taken from many sources carefully and accurately [29]. However, to get more accurate results, it is necessary to replace the default value with a locally specific value from the site so we will get results more accurately and can be accountable. From available data, the dose for receptors and pathways of exposure is calculated according to scenarios. The scientific calculation of exposure pathways will be explained in the subsection below.

The exposure scenario parameters are written in Eq. (4) [35].

$$DINH = IR \times TIC_j \times DCINH_j \tag{4}$$

Where:

DINH = The effective respiratory radiation dose related to TENORM disposal (mSv)
IR = Inhalation rate ($m^3\ s^{-1}$)
TIC_j = Average concentration of the radionuclide over time (Bq-s m^{-3})
$DCINH_j$ = Respiratory effective dose factor for the radionuclides (mSv Bq^{-1})

Compliance with regulatory standards

Throughout the study, efforts were made to ensure that the methodology adhered to both Indonesian regulations and international guidelines for TENORM waste management. Regulatory standards, including Indonesian Government Regulation No. 101/2014 and IAEA safety requirements, were closely followed to guarantee that the landfill design complied with all environmental and public health safety standards [15,24].

RESULTS AND DISCUSSION

Results

This study analyzes radiation safety for a Class II landfill designated to dispose of TENORM by-products deriving from the tin sector in West Bangka Regency. After entering the input parameters, which are written in Table 2 into the software, it is processed, and the results obtained are analyzed for the safety assessment of landfill facilities and the surrounding environment. The picture below shows the dose value obtained by people around the site at 200 meters (assumed nearest residential) from the contamination zone.

This study used Resrad software to calculate the received dose value by residents who stay 200 meters from the center of the landfill facility before the construction is relatively safe. The dose is 4.88×10^{-3} mSv/year after the facility closed from all pathways.

After the software stops computing, the resulting graph shows an interesting pattern. Figure 5 shows that the shape of the graph initially increases very slightly from 0 years to 1,343 years because the parent radionuclides begin to decay and produce new daughter radionuclides, which will emit radiation. Then decreased in year 1,368 and slumped from year 3,000 to year 5,000. Then, the dose will increase starting from year 5,032 to year 29,265. On the 29,265th year, the dose peaks; society will get 0.40537 mSv/year, then declines gently until 50,000 years with a progressively gentler decline.

The simulation in 50,000 years depicted in Fig. 5 may be too long for human life, so the graph is shortened to 125 years as depicted in Fig. 6. At the moment after close, the dose is 4.88×10^{-3} mSv/year or equivalent excess probability of cancer 1:4,096,682 the dose increased slightly, and the shape is close to linear. The dose is 4.90×10^{-3} mSv/year in the 50th year and 4.92×10^{-3} mSv/year in the 100th year. So at 125th, it reaches 4.93×10^{-3} mSv/year or an equivalent excess probability of cancer 1:4,056,795 at 125th year.

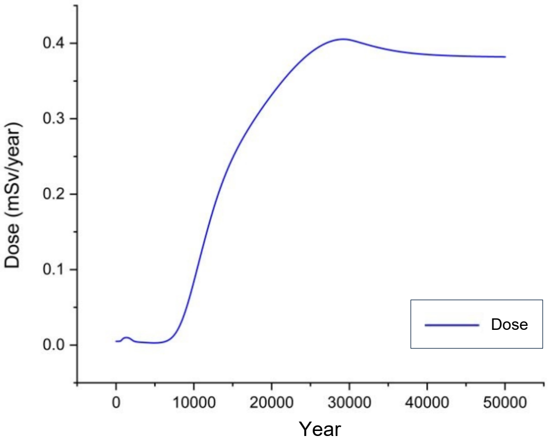

Fig 5. The total dose graph will be received at 200 meters from the center of the landfill until 50,000 years.

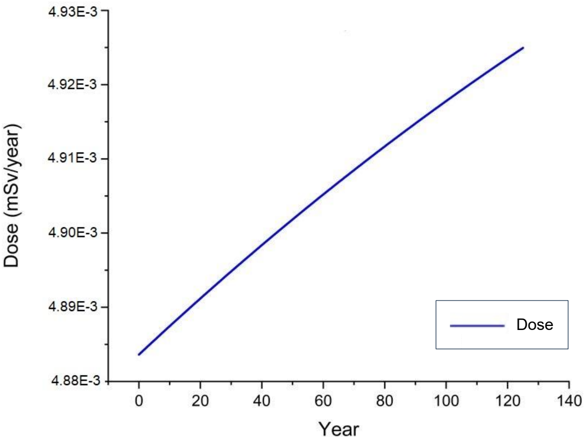

Fig 6. The total dose graph will be received at 200 meters from the center of the landfill until 125 years.

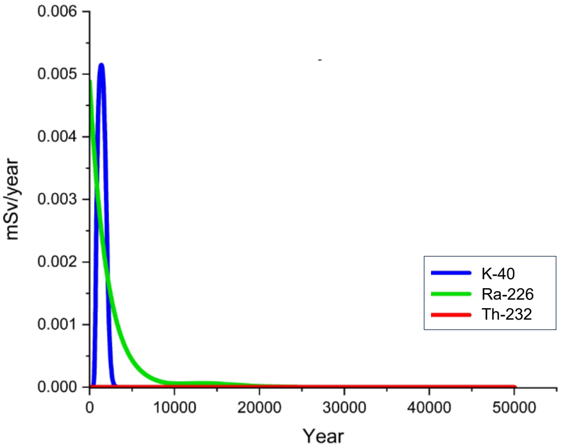

Fig 7. The dose graph will be received at 200 meters from the center of the landfill affected by K-40, Ra-226, and Th-232.

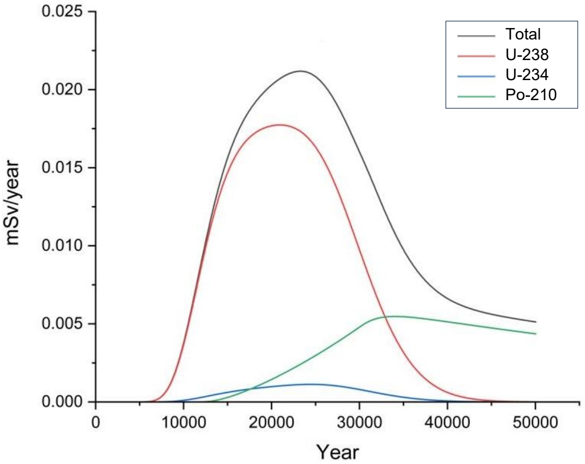

Fig 8. The dose graph will be received at 200 meters from the center of the landfill affected by U-238 and its progeny.

The dose caused by K-40 radionuclide at a distance of 200 meters, as shown in Fig. 7, begins at 0 mSv/year and dramatically increases to 5.15 x 10^{-3} mSv/year by the 1,368th year. This rise is attributed to the movement and distribution of K-40 material rather than a significant loss through decay.

The total dose from Ra-226 and its decay products starts at 4.88 × 10^{-3} mSv/year, with an associated cancer risk of 2.44 × 10^{-7}. The dose decreases sharply until about 10,000 years, reaching 7.30 × 10^{-5} mSv/year, and then rises slightly around 14,000 years, peaking at 1.27 × 10^{-4} mSv/year before declining again toward 50,000 years. For Th-232 and its progeny, the dose remains near 0 mSv/year until around 43,000 years, then rises to 8.80 × 10^{-6} mSv/year by the 50,000th year.

Figure 8 illustrates that the total dose from U-238 and its decay products remains nearly zero until approximately the 6,000th year. After that point, it starts to increase, reaching a peak of 0.024 mSv/year at the 24,000th year, which corresponds to an excess cancer risk of 1.200 × 10^{-6} (or 1 in 833,333). Following this peak, the dose drops sharply to 0.010 mSv/year by the 36,000th year and continues to decline more gradually to 0.0056 mSv/year by the 50,000th year.

The dose from U-238 peaks at 0.017735 mSv/year in the 20,800th year, resulting in an excess cancer risk of 8.87 × 10^{-7} (or 1 in 1,127,000) before dropping to 0.000007 mSv/year by the 50,000th year. Po-210 and Ra-226 exhibit similar trends, with doses near zero until the 9,000th year. Both peaks are in the 29,700th year at 0.004 mSalv/year and 0.004 mSv/year, respectively, corresponding to excess cancer risks of 1.96 × 10^{-7} (or 1 in 5,098,000) and 1.77 × 10^{-7} (or 1 in 5,656,000). These values then decrease to 0.003 mSv/year for Po-210 and 0.003 mSv/year for Ra-226 by the 50,000th year.

U-234 and Th-230 show a gradual increase, with U-234 peaking at 0.0011 mSv/year in the 24,500th year and Th-230 peaking at 0.0003 mSv/year in the 40,300th year. These correspond to cancer risks of 1 in 17,700,000 for U-234 and 1 in 80,000,000 for Th-230. By the 50,000th year, their doses decrease to 0.000001 mSv/year for U-234 and 0.0002 mSv/year for Th-230.

Figure 9 depicts the change in radionuclide concentrations at the primary contamination site over time. The concentration of K-40 decreases from an initial value of 0.527 Bq/g at t = 0 years to about 0.110 Bq/g at t = 25 years and 0.001 Bq/g at t = 100 years. It continues to decrease asymptotically towards 0 Bq/g by 500 years, remaining negligible up to 50,000 years. This rapid decline is due to K-40's high leachability.

Ra-226 starts at 4.744 Bq/g at t = 0 years, increases slightly to 4.751 Bq/g at t = 25 years and 4.7697 Bq/g at t = 100 years, then drops to 4.6875 Bq/g by t = 1,000 years. At t = 10,000 years, it decreases to 0.6425 Bq/g, further reducing to 0.0083 Bq/g at t = 25,000 years, and becomes negligible by t = 50,000 years.

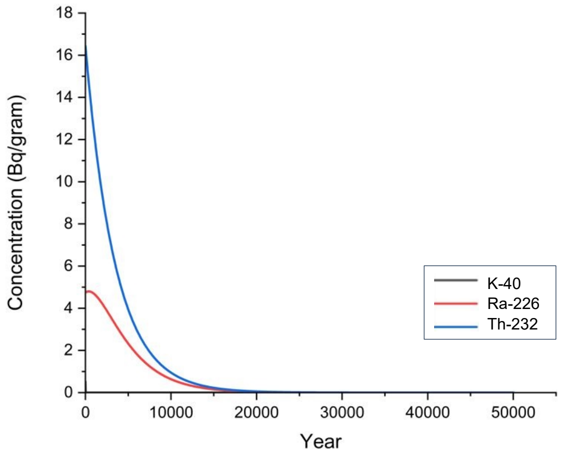

Fig 9. Radionuclides activity concentration as time function at primary contamination.

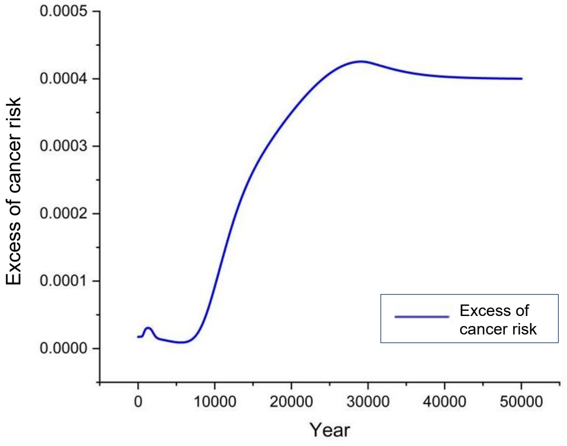

Fig 10. Excess cancer risk will be received 200 meters from the center of the landfill.

Th-232 begins at 16.431 Bq/g at t = 0 years, slightly decreases to 16.317 Bq/g at t = 25 years, and 15.979 Bq/g at t = 100 years, continuing to drop to 14.293 Bq/g at t = 500 years and 12.348 Bq/g at t = 1,000 years. By t = 10,000 years, it falls to 0.9370 Bq/g and further to 0.013 Bq/g at t = 25,000 years, approaching zero by t = 50,000 years.

Figure 10 gives an overview of the effect of landfills on the excess cancer risk at a distance of 200 meters from the landfill center. The risk remains relatively stable from 0 to 415 years, at around 1.75×10^{-5}, then gradually increases to 3.05×10^{-5} by the 1,245th year. It drops again to 8.93×10^{-6} by the 5,569th year before rising sharply to 4.25×10^{-4} in the 29,265th year. By the 50,000th year, the risk slightly decreases to 4.00×10^{-4}.

Discussion

Previous studies using RESRAD Offsite 4.0 and similar modeling tools have assessed the environmental and health risks of TENORM waste disposal. Notably, Caffrey and Cheng [29,35] conducted simulations to estimate radiation doses in landfills, providing valuable references. Their work, alongside other similar studies, has contributed to a deeper understanding of TENORM's potential impact on ecosystems, enhancing the reliability and accuracy of current radiological risk assessments.

Environmental factors, such as the natural degradation of landfill barriers, significantly affect the long-term management of TENORM waste. Studies by Meegoda and Dwipayana [21,34] show how climate conditions, including rainfall and groundwater movement, influence leachate migration and the spread of TENORM materials. These findings stress the importance of considering natural processes when evaluating landfill barrier safety. Additionally, IAEA Safety Series No. 111-G-3.1 provides essential guidelines for landfill safety. The Case study by Ali et al. [12] on petroleum waste offered valuable insights into managing TENORM waste under similar environmental conditions.

The pattern in Fig. 5 represents the gradual degradation of the landfill facility. Initially, the graph shows an increase in radiation due to the decay of parent radionuclides and the emission of radiation from daughter radionuclides. After 5,032 years, the radiation dose increases sharply due to accelerated damage to the landfill facility, which deteriorates much faster than the half-lives of Uranium and Thorium, which span billions of years. By the 29,265th year, it is likely that the facility has been fully destroyed, causing the peak dose. Following this peak, the radiation dose declines gradually, likely due to changing environmental conditions and the system's stabilization after the landfill's destruction.

Figure 6 demonstrates that the dose from K-40 initially rises due to its distribution, not decay, reaching the peak at 1,368 years. This risk is minimal, affecting 1 in 3.88 million. The dose then declines towards 0 mSv/year by 3,000 years as K-40 dissipates. Similarly, the dose from Ra-226 decreases significantly over time, with a small increase around 14,000 years before stabilizing. For Th-232, the dose remains negligible until 43,000 years, rising slightly by 50,000 years, reflecting an extremely low cancer risk.

Figure 8 shows that the dose from U-238 and its decay products remains low until around the 6,000th year, which gradually increases. It happens because the landfill facility begins to be destroyed by age, and uranium has a very long half-life, so the reduction in exposure can be negligible.

Figure 9 illustrates the changes in radionuclide concentrations at the contamination site over time. K-40 rapidly decreases from 0 years to 100 years and approaches zero by 500 years due to its high leachability. Ra-226 initially increases slightly but then declines gradually, becoming negligible by 50,000 years. Th-232 decreases steadily, dropping from 16.431 Bq/g at t = 0 years to near zero by 50,000 years. These trends highlight the varying decay rates and leachability of each radionuclide over time.

Figure 10 presents the excess cancer risk from radiological exposure to the facility. The exposure is relatively very small, but the cancer risk must be a concern for the public because it involves aspects of human health. Cancer is a dangerous disease that is a stochastic risk from radioactive radiation. Therefore, in the safety assessment, we need to reduce this cancer risk as much as possible. The smaller the dose society gets, the better for human health, so the dose must be controlled.

The dose increases on the 415th year and then decreases at the 1,245th year because of the effect of K-40 leaching. The dose increased drastically starting from the 415th to 1,368th, so it is impacted to excess of cancer risk at 415th year. Then, K-40 is easy to leach from landfills into the environment so that the dose received by humans will increase and then decrease because the K-40 will run out [36].

CONCLUSION

This research highlights the essential role of managing TENORM waste to reduce environmental and health hazards in Bangka Island. As tin mining activities in Indonesia continue to grow, it is crucial to implement a systematic strategy for handling TENORM waste to meet regulatory requirements and ensure long-term sustainability. By using RESRAD Offsite 4.0, we assessed the radiological safety of a proposed Class II landfill and confirmed that its design is capable of effectively containing radioactive materials within safe exposure thresholds.

The simulation results show that, under the maximum exposure scenario 200 meters from the landfill center, the highest radiation dose the public could receive is estimated at 0.40537 mSv/year in the 29,265th year, well below the 1 mSv/year limit set by BAPETEN. Furthermore, the additional cancer risk at this peak exposure is projected to be 4.25×10^{-4}, which is within globally accepted safety standards. This indicates that the landfill design offers a sufficient safety margin for long-term environmental protection. The gradual increase and subsequent decrease in radiation exposure over tens of thousands of years demonstrate the effectiveness of the engineered barriers in slowing down and minimizing the movement of radioactive materials.

Although alternative waste management strategies may be proposed, this study supports the selection of a Class II landfill, highlighting its ideal balance of cost-efficiency and compliance with safety standards. While a Class I landfill provides slightly better containment, it involves much higher construction and maintenance costs without offering a corresponding risk reduction. Additionally, the Class II landfill design for TENORM waste has been successfully implemented and proven to ensure radiation safety in several countries across the globe. This practical experience worldwide further reinforces the argument for opting for the Class II landfill solution, and this facility is proven safe.

Future research should focus on barrier technology, recycling technology, and determining local parameters like coefficient distribution at that location. Collaboration with any stakeholders is recommended to support proper waste disposal and environmental protection.

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AUTHOR CONTRIBUTION

We confirmed that all authors are equal as the main contributors in this paper. All authors reviewed and approved the final version.

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