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The Development of a DISPERSIA Code Program-Air Dispersion Program for Radiological Dose Assessment of Nuclear Facilities

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A B S T R A C T

The DISPERSIA-BRIN program, along with its sub-programs STDISPERSIA and WRDISPERSIA, was developed to enable swift and effective radiological analysis, essential for rapid decision-making during nuclear accidents. These programs were validated against SIMPACT version 1.0 confirming their accuracy and reliability. Python was selected as the primary programming language due to its simplicity and versatility. DISPERSIA-BRIN incorporates geospatial analysis tools, allowing researchers to visualize the radioactive material concentration and the dose impact on polar grids surrounding the nuclear facility. The program models the dispersion of concentrations and their dose effects, assessing their interaction with humans, livestock, and plants. This helps to identify high-dose areas, vulnerable populations, and emergency planning zones. A case study involving a hypothetical Nuclear Power Plant and site demonstrated DISPERSIA-BRIN's capability to accurately calculate and visualize radionuclide dispersion, aiding in the identification of high-radiation areas.

1. INTRODUCTION

Nuclear reactor facilities are important sources of energy but also have the potential to release radionuclides into their surrounding environment. The development of nuclear infrastructure, particularly regarding site and environmental aspects, is a crucial step in preparing for constructing Nuclear Power Plants (NPPs) in the early stages, or phases 1 and 2 [1]. At this stage, the key milestones include the decision to initiate the NPP program and the readiness to conduct tenders. Determining the appropriate site and carefully managing the environment is essential to ensure the safety and sustainability of the NPP program.

Many site studies have been conducted in Indonesia, and many more are planned to be built [2–5]. These studies provide critical data that assist the government in initiating NPP construction. However, the need for adequate, fast, and readily usable analytical tools becomes increasingly urgent in facing these challenges. Exposure to radiation generated by these radionuclides can significantly impact human health and the environment [6]. Therefore, calculating the radiation dose from radionuclides released by nuclear reactor facilities is crucial for identifying and reducing associated risks. These tools must provide accurate decisions regarding the radiological impact of NPP construction, ensuring the safety of the environment and the public.

One of the main challenges in implementing radiological analysis is the difficulty in estimating

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source terms and their application into dispersion models at specific sites. Approximation source terms are essential to ensure reliable dispersion models. Although many commercial analysis programs are available for radiological analysis, such as PC-COSYMA, PC-CREAM, SIMPACT, and HYSPLIT, most are not directly integrated with the specific conditions of the locations where NPPs will be built [7, 8].

This paper presents analytical equipment that combines source terms and dispersion with specific environmental conditions. These tools are designed to provide quick and accurate solutions and make precise decisions in NPP construction. Based on our local experience, this equipment can also be used as a quick analysis for newcomer countries considering building NPP so that the newcomer can be better prepared to face environmental and safety challenges in the early stages of NPP nuclear infrastructure development.

This study aims to develop a computer program capable of quick and simple estimation of the radiation dose from released radionuclides from nuclear reactor facilities using dispersion methods. This program is expected to provide estimates of the radiation dose received by the public and the surrounding environment of nuclear facilities, thus serving as a basis for designing effective risk control measures.

The DISPERSIA-BRIN will focus on developing algorithms for calculating the radiation dose from the release of radionuclides, considering various parameters such as types of radionuclides, meteorological conditions, topography, and environmental characteristics. The program will be developed using Python and include modules for calculating radionuclide dispersion and estimating radiation doses.

2. METHODS

The program is mainly developed in source term calculation, dispersion, and dose assessment.

1. Source Term Calculation

This part involves determining the quantity and characteristics of radionuclides released from nuclear facilities. It includes evaluating the types of radionuclides, their activity levels, and the conditions under which they are released. Accurate source term calculation is crucial as it sets the foundation for the subsequent dispersion and dose assessment processes.

2. Dispersion

This section focuses on modeling how the released radionuclides spread through the environment. It considers meteorological conditions (wind speed, direction, atmospheric stability), geographical features (terrain, water bodies), and other environmental characteristics. The dispersion model predicts the movement and concentration of radionuclides over time and distance, providing a detailed map of their distribution in the environment.

3. Dose Assessment

The final part assesses the potential radiation dose received by individuals and the environment due to the dispersed radionuclides. This part involves calculating the exposure levels based on the dispersion data, considering different exposure pathways (inhalation, ingestion, direct radiation). The dose assessment provides critical information on the potential health impacts and environmental risks, helping to design effective risk control measures and ensuring compliance with safety standards.

2.1 Source Term

In general, the source term is calculated to determine the release rate of radionuclide to the environment so that the pathway of the release includes gap, early in vessel, ex-vessel, late in vessel, and containment can be followed. The fraction release of each stage follows the "Soffer" article as in Table 1 [9, 10].

Table 1. The Fraction Release of Radionuclides

Radionuclide	Inventory	Gap	Early in Vessel	Ex-Vessel	Late in Vessel
^{85}Kr	2.97E+15	0.05	0.95	0	0
^{133}Xe	3.76E+17	0.05	0.95	0	0
^{131}I	3.37E+17	0.05	0.35	0.25	0.1
^{137}Cs	3.38E+16	0.05	0.25	0.35	0.1
^{132}Te	2.75E+16	0	0.05	0.25	0.005
^{89}Sr	2.55E+16	0	0.02	0.1	0
^{99}Mo	6.36E+17	0	0.0025	0.0025	0
^{95}Zr	5.95E+17	0	0.0005	0.005	0

The leakage from containment to the environment can be calculated using Eq. 1 [9, 11] :

$$L(t) = \frac{B_0 X}{2400} \cdot \frac{1}{\left(\lambda + \frac{X}{2400}\right)} \cdot \left[1 - exp\left[-\left(\lambda + \frac{X}{2400}\right) t\right]\right] \quad (1)$$

where $L(t)$ is the leakage rate in Bq/hour, B_0 is the radionuclide concentration in Bq. X is the leakage percentage per day, λ is the decay rate of the radionuclide in hours, and t is the release duration in hours.

2.2. Atmospheric Dispersion

The release from containment to the environment will be diluted or dispersed into an atmosphere following Gaussian Distribution as in Eq. 2 [11–16]:

$$X(x,y,z) = \frac{Q_o}{2\pi\sigma_y\sigma_z u} exp\left[-\frac{y^2}{2\sigma_y^2}\right] * \left[\exp\frac{(z-H)^2}{2\sigma_z^2} + exp\frac{(z+H)^2}{2\sigma_z^2}\right] \quad (2)$$

where $X(x, y, z)$ is the concentration in air activities at the point of x, y, z in Bq /m^3, x is the distance from the source in meter, y is the distance perpendicular to horizontal wind direction in meter, z is the distance perpendicular to vertical wind direction in m, H is the stack effective height in m, σ_y is the horizontal std deviation of Gauss distribution in m, σ_z is the vertical std deviation of Gauss distribution in m, u is the wind speed in m/s, Q_o is the release rate in Bq/second.

2.3. Radiation Dose

The radiation dose concept is the amount of radiation energy absorbed by an object or organism. In the context of nuclear facilities, radiation doses can originate from various sources, including radionuclides released during operational processes or accidents. Exposure to radiation doses can have short-term and long-term effects on human health, depending on the level of exposure and the type of radiation involved.

Characteristics of radionuclides released from reactor facilities can have various properties that influence their environmental behavior. These properties include the type of radionuclide, half-life, type of emitted radiation, and ability to diffuse or spread in the surrounding environment. Understanding these characteristics is vital for calculating radionuclide dispersion and estimating radiation doses received by affected populations. The effective radiation dose for humans is calculated using the accumulation of external exposure or cloud model, deposition and resuspension calculation model, and inhalation dose model, following the method presented by Pane [11, 17]. The cloud model accommodates the interaction between radionuclides as a radioactive cloud that reaches the ground and the human tissue and could be formulated as follows [11, 16].

$$E_{im} = X(x, y, z) DF_M O_f \tag{3}$$

where E_{im} is the radioactive cloud model annual dose, $X(x, y, z)$ is the average annual concentration of radionuclide in air in Bq/m^3, DF_M is the effective immersion dose coefficient in Sv/a per Bq/m, O_f is the annual fraction of the hypothetical critical group exposed to this external dose. The deposition model accommodates the dose of dispersed radioactive materials that fall into the ground, which could be calculated in this formula [11, 16]:

$$d_i = (V_d + V_W) * X(x, y, z) \tag{4}$$

where d_i is the average daily deposition rate in Bq.m-2.day, V_d is the dry deposition coefficient in m/day, and V_W is the wet deposition coefficient in m/day. The inhalation dose model calculates the radionuclides that reach the ground level and could be inhaled by humans and cause internal radiation. The annual inhalation dose (E_{inh}) is formulated as follows [11, 16].

$$E_{inh} = X(x, y, z) DF_{inh} R_{inh} \tag{5}$$

where DF_{inh} is the inhalation dose coefficient in Sv/Bq, and R_{inh} is the rate of inhalation in m^3/year. The individual dose that directly affects the human body is the accumulation of cloud, deposition, and inhalation.

3. DESIGN AND IMPLEMENTATION OF PROGRAM

The radiation dose calculation algorithm will consider various parameters, including radionuclide type, half-life, wind speed, wind direction, and other factors affecting radionuclide dispersion in the environment. Dispersion Models will be integrated into the program as part of the calculation algorithm. Model parameters, such as wind speed, wind direction, and environmental characteristics, will be input by the user or taken from external data sources. Based on these parameters, the program will calculate the dispersion patterns of radionuclides in the environment and generate estimates of radiation doses received by affected populations. The DISPERSIA-BRIN program is based on Python.

The program is divided into several sub-program modules based on the program functions. The source term module manages the source term data, consisting of radionuclides type and Qo value. The source term data could be calculated with the RelVol model [9] module or manually input. The released source term is calculated within a user-defined release time using the STDISPERSIA sub-program. The meteorological data module processes the wind data, including the wind speed and direction. The dispersion calculations assumed the atmosphere has one stability condition. Therefore, the wind data will be seasonally averaged for the dispersion calculations. The population and environmental data module create or modifies the input data. The data needs to be divided into sectors based on the radius and direction from the assessed location point. The dispersion module calculates the dispersed radioactive concentrations in the air for each sector using source terms and meteorological data. This module also calculates the human individual effective dose based on cloud, deposited, and inhaled dose. The environmental dose for green vegetables, root vegetables, sheep, beef, and cereals are calculated in this module. The risk assessment module reads the population and environmental data and uses the calculated dose from the dispersion module output to calculate the risk assessment for each sector. The geospatial module is a utility module that could be used to make a radial sectoral plot of input and output from the module.

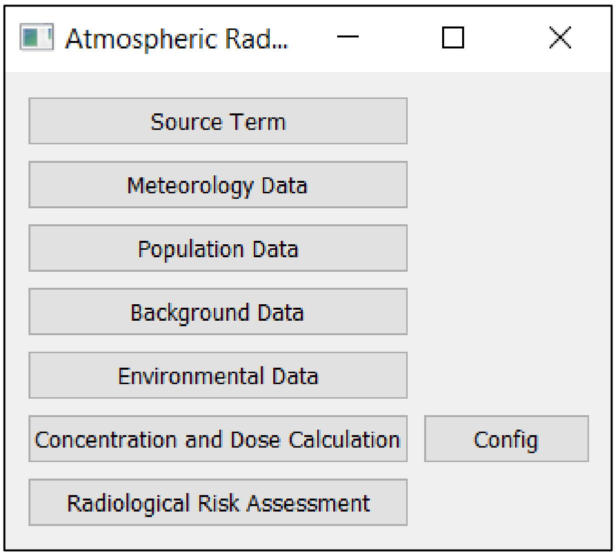

Fig. 1. The Dispersia-BRIN GUI

This model is represented in a GUI input program, as shown in Fig. 1. The source term is determined based on the duration of the release, referred to as the "release time." Conversely, the impact on the receiver, who will be affected by the radioactive material, depends on the length of their exposure to the radiation, known as the "exposure time." Meteorological data, population, background, live stocks, and plant were manually input, saved, opened, plotted, and modified. The dispersion module was developed to estimate the concentration distributed on geospatial and individual doses and, finally, dose assessment. Further development will continue to estimate the radiological risk to health.

Figure 2 shows the flow of dispersion calculation in this program. This program needs source term, wind, population, environment, and background radiation data as input for the calculation. The dispersed radioactive concentration is calculated for each radionuclide based on source term and wind data. The distributed radionuclide concentration is then modeled for the air-concentrated model in the form of inhaled dose, external exposure dose, and deposited dose model. Both models were assumed to affect humans directly and calculated as individual human doses. The distributed concentration is also assumed to be deposited in the environment humans might consume, such as vegetables and livestock. The deposited environment concentration is calculated as an individual environmental dose for each vegetable and livestock. The individual human dose is then calculated with the population density to obtain the cumulative human dose. If the environmental data is available in the study area, the vegetable and livestock data will be calculated with corresponding individual environmental doses as cumulative ingested doses. The total human radiological risk is the summation of the cumulative human dose and environmental dose.

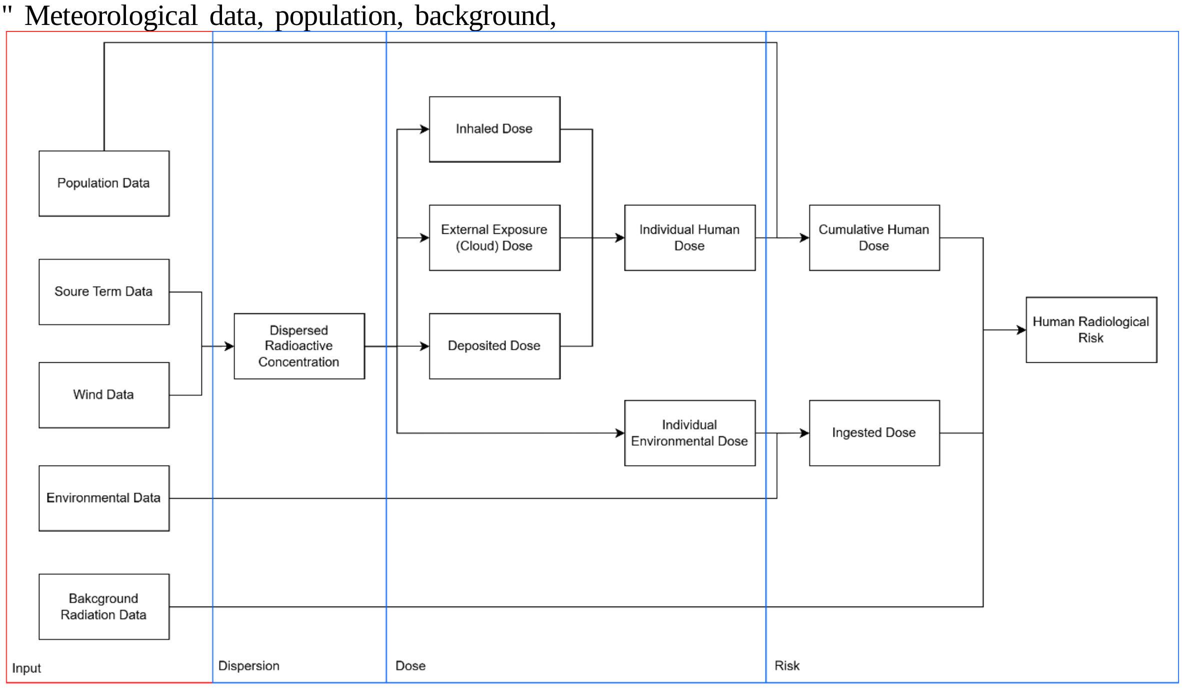

Fig. 2. The flowchart of DISPERSIA-BRIN Program

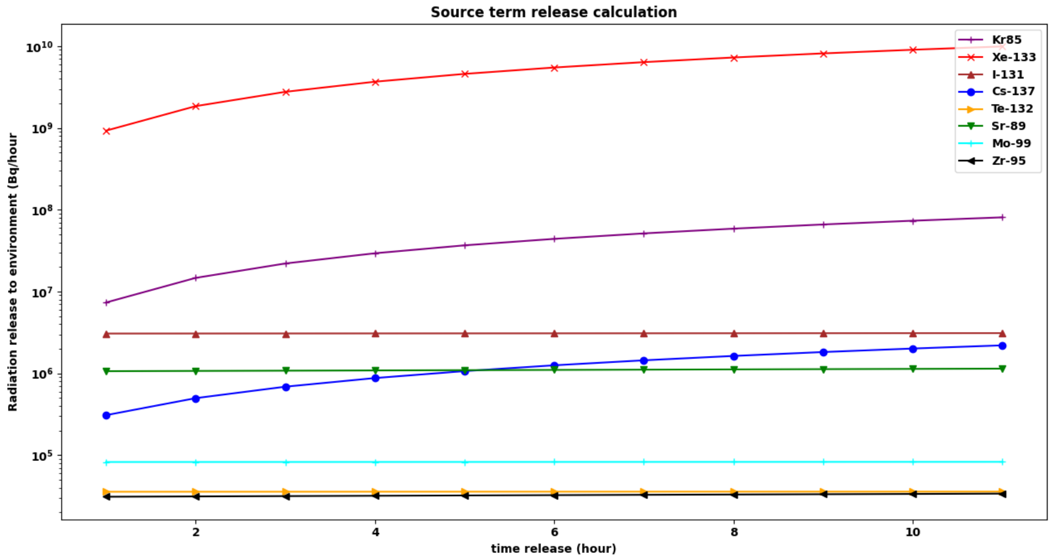

Fig. 3. The cumulative source term release within 1 to 12 hours.

In terms of validation, the program was compared to the code program of SIMPACT version 1 at a certain stage of the program in calculating the concentration and dose. This validation test used the same wind, source term, and other parameters to make the result comparable.

The DISPERSIA-BRIN concentration yields an identical result to the SIMPACT. This result implies that the dispersion algorithm in the DISPERSIA-BRIN is reliable and could deliver a good result. The dose calculation result of DISPERSIA-BRIN yields the same result as the SIMPACT, especially at the smaller radius. At the larger radius, the Dispersia-BRIN tends to give an overestimated result compared to the SIMPACT due to dose coefficient differences. However, the result generally shows good agreement, as shown in Tables 2 and 3.

Table 2. The Concentration Validation

Source term	Distance (m)	Concentration	
		Dispersia	Simpact
^{131}I	500	$4.04 \text{ x } 10^{-1}$	$4.04 \text{ x } 10^{-1}$
	1000	1.29×10^{0}	1.29×10^{0}
	2000	9.15×10^{-1}	9.15×10^{-1}
	5000	2.76×10^{-1}	2.76×10^{-1}
	10000	9.34×10^{-2}	9.34×10^{-2}
	20000	3.02×10^{-2}	3.02×10^{-2}
	35000	1.20×10^{-2}	1.20×10^{-2}
	50000	6.65×10^{-3}	6.65×10^{-2}
^{137}Cs	500	4.52×10^{-2}	4.52×10^{-2}
	1000	1.45×10^{-1}	1.45×10^{-1}
	2000	1.02×10^{-1}	1.02×10^{-1}
	5000	3.09×10^{-2}	3.09×10^{-2}
	10000	1.05×10^{-2}	1.05×10^{-2}
	20000	3.38×10^{-3}	3.38×10^{-3}
	35000	1.34×10^{-3}	1.34×10^{-3}
	50000	7.44×10^{-4}	7.44×10^{-4}

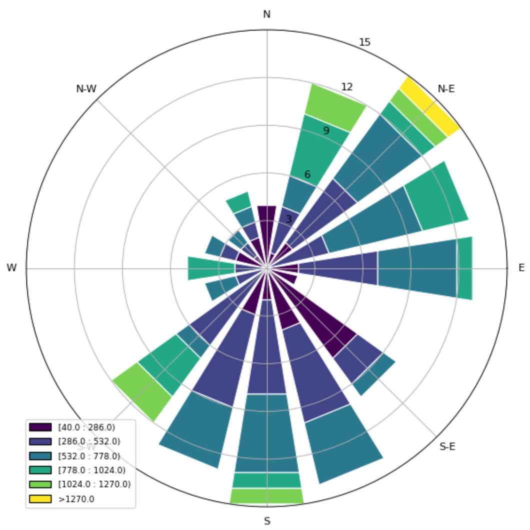

Fig. 4. The wind direction and speed data in m/s of the ULA site using WRDISPERSIA

Table 3. Dose Validation

Source term	Distance	Inhalation Dose	
		Dispersia-BRIN	Simpact
^{131}I	500	4.22×10^{-5}	4.22×10^{-5}
	1000	1.35×10^{-4}	1.35×10^{-4}
	2000	9.55×10^{-5}	2.85×10^{-5}
	5000	2.88×10^{-5}	3.16×10^{-6}
	10000	9.75×10^{-6}	6.94×10^{-7}
	20000	3.16×10^{-6}	5.51×10^{-7}
	35000	1.25×10^{-6}	5.51×10^{-7}
	50000	6.94×10^{-7}	3.75×10^{-7}
^{137}Cs	500	4.72×10^{-6}	4.72×10^{-6}
	1000	1.51×10^{-5}	1.51×10^{-5}
	2000	1.07×10^{-5}	1.07×10^{-5}
	5000	3.22×10^{-6}	3.22×10^{-6}
	10000	1.09×10^{-6}	3.53×10^{-7}
	20000	3.53×10^{-7}	7.77×10^{-8}
	35000	1.40×10^{-7}	6.16×10^{-8}
	50000	7.77×10^{-8}	4.19×10^{-8}

4. CASE STUDY: HYPOTHETICAL NPP SITE

The study was done in a hypothetic site the Ujung Lemah Abang (ULA Site), where a 1000 MWe LWR-type NPP will be built. We will investigate the largest dose of radionuclides Kr-85, I-131, and Cs-137 to determine the critical location of the release of Large Break Loss of Coolant Accident to the NPP.

4.1. Source Term

For the Large Break Loss of Coolant accident, we assumed that the core inventory would release as much as 70% and that the spray cooling system would be working. The source term (ST) release is assumed to occur for 12 hours with 24 hours of exposure time. This case study used source term inventory data from ORIGEN2.1. The source term is estimated using the STDISPERSIA submodule, as shown in Table 4 and Fig. 3.

Table 4. The source term data

Radionuclide	Inventory (Bq)	ST in Containment (Bq)	ST in Environment (Bq)
^{85}Kr	2.97×10^{15}	4.23×10^{13}	2.15×10^{5}
^{133}Xe	6.29×10^{18}	5.36×10^{15}	2.14×10^{4}
^{131}I	6.29×10^{18}	1.77×10^{13}	8.22×10^{0}
^{137}Cs	1.74×10^{17}	1.77×10^{12}	2.23×10^{0}
^{132}Te	4.44×10^{18}	2.06×10^{11}	7.77×10^{-1}
^{89}Sr	3.38×10^{18}	6.12×10^{12}	3.07×10^{1}
^{99}Mo	5.92×10^{18}	4.77×10^{11}	1.03×10^{1}
^{95}Zr	5.55×10^{18}	1.78×10^{11}	6.92×10^{-1}

Figure 4 shows the windrose data of the ULA site used in this study. The windrose data showed the general wind direction and speed for all directions in m/s. The wind data is sampled for each hour. Each color in the windrose represents the wind speed range in the legend, and the length of each shows the stacked frequency of occurrence. For the ULA site, there are 2 major wind directions, the NE and S direction. The ULA site is located near the shoreline area. Thus, the NE wind direction represents the sea breeze that blows from the ocean and the S wind direction is the land breeze that blows from the Muria Mountain south of the ULA site. The land breeze has a higher frequency than the sea breeze. However, the sea breeze has the highest wind speed of more than 1270 m/s.

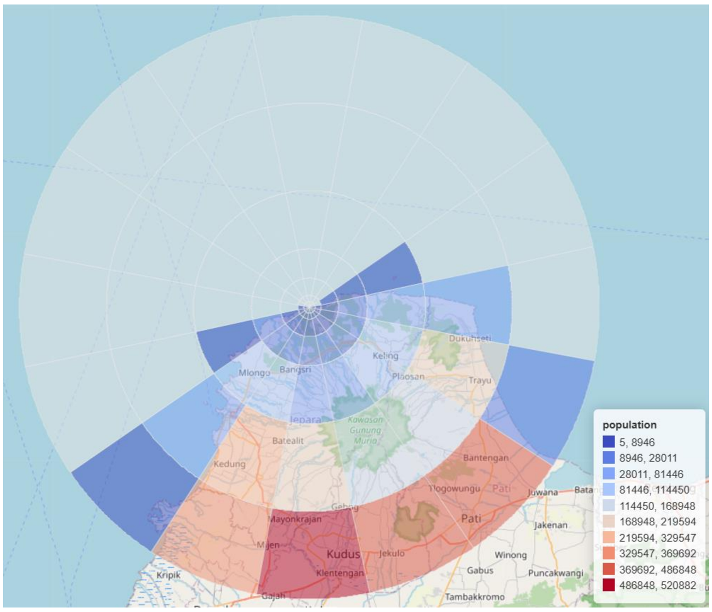

Fig. 5. The population distribution plot

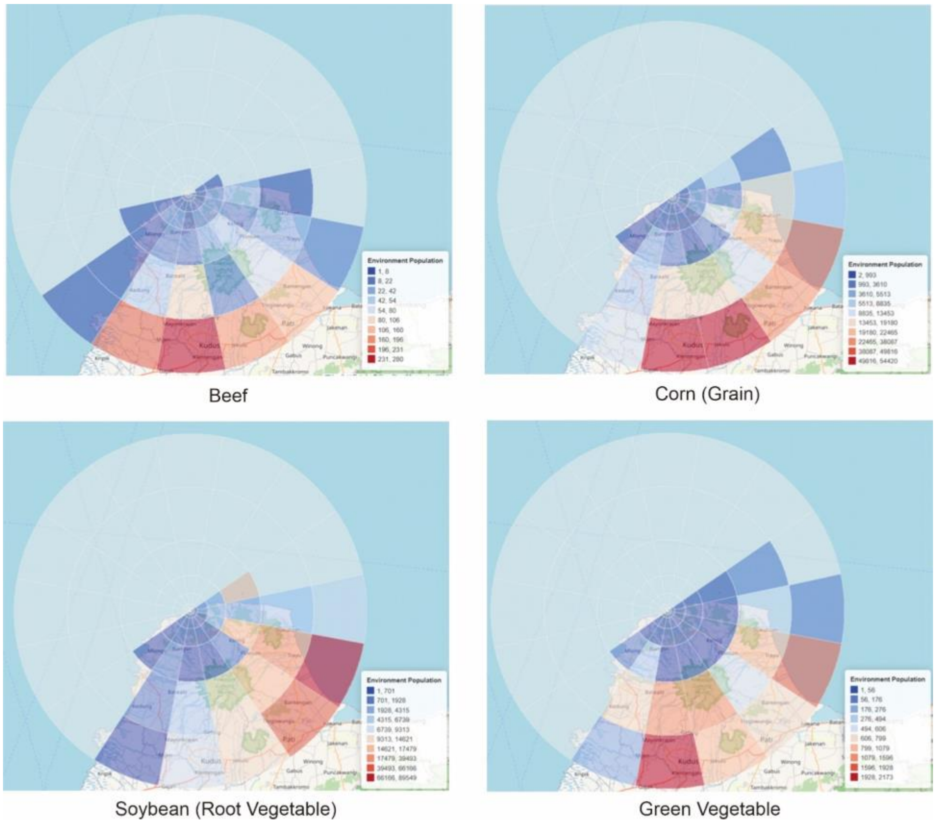

Fig. 6. The environment distribution plot

The people and environment data are divided into sectors based on a predefined radius and direction before inputting into the DISPERSIA-BRIN. Figure 5 shows the population distribution plot and Fig. 6 shows the environmental data plot at the ULA site. The analysis radius is configured to be the same as the data, divided into 1, 2,5, 10, 20, 35, and 50 km from the point of interest. In this study, the chimney height is assumed to be 40 m, the average deposition speed for radionuclides is assumed to be 0.005, and the mean adult annual breathing rate is assumed to be 8030.

Figure 7a shows the calculated individual human dose result from the program in Sv. The dose is the summation of inhaled, exposed, and deposited dose that might affect the human directly. The result showed that the area at a 1 to 2 km radius has a high radiological dose of more than 1 μSv, with a maximum of 9.3 μSv. Figure 7b shows the dose distribution vs distance graph for all directions. The dose is reduced exponentially as the distance from the center increases, which implies the result is reliable. The individual dose is also calculated for each environment data.

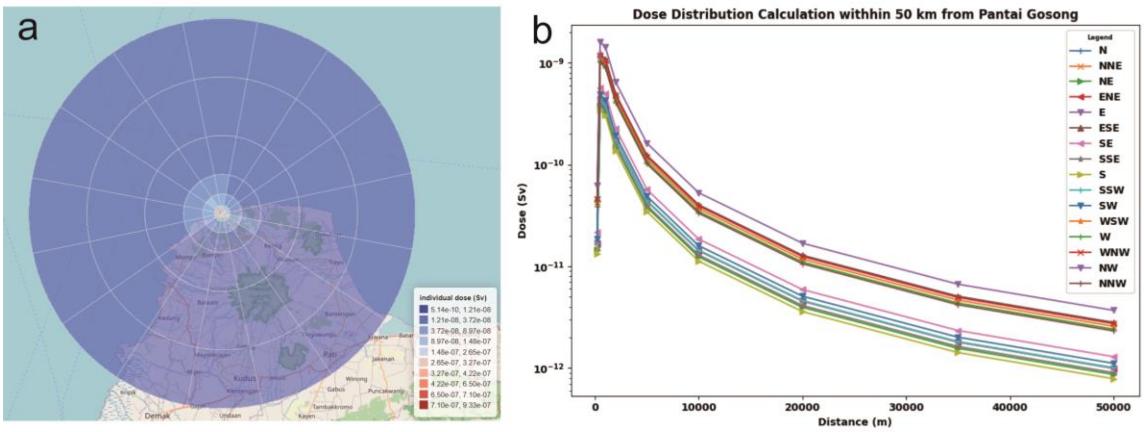

Fig. 7. (a) The calculated individual dose, (b) The individual dose vs distance for all direction

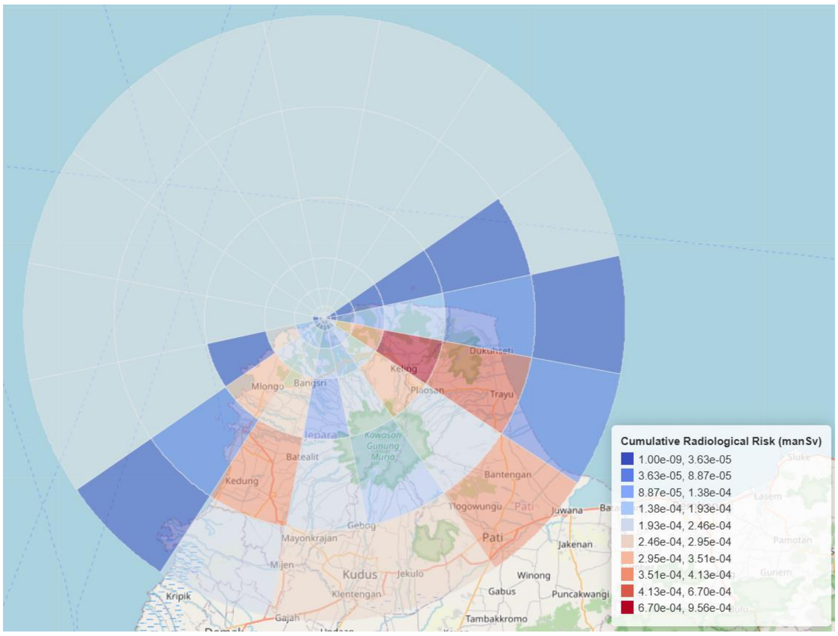

Fig. 8. The cumulative radiological risk result in ULA site

The calculated individual dose for human and environmental data is then multiplied with the human and environmental population data to calculate the cumulative human and environmental dose. The cumulative radiological risk is shown in Fig. 8, which is the summation between the cumulative human and environmental doses. The result showed the area with a dense population in the south part of the study area has a moderate to high-risk value of 250 – 450 manµSv. For most of the area, the risk is relatively low with a value of 0 to 250 manµSv. The area in the ESE direction at near 20 km radius has a high-risk value with a value of 955 manµSv, although the population is low. This result is due to the wind data distributions. Wind speed and direction are critical parameters in radioactive concentration dispersion calculations and could affect the result significantly.

5. DISCUSSION

The development of the DISPERSIA-BRIN programs aims to facilitate swift and effective radiological analysis, which is crucial for making rapid decisions during an accident. The basic principle of the programming is the release of radioactive materials from the accident source (calculated with STDISPERSIA), which results in the presence of radioactive material concentration in the air, distributed according to wind direction and speed (visualized with WRDISPERSIA). The distribution magnitude is then calculated along the radial direction, both in the air as a radiation cloud and through inhalation or deposition, which subsequently interacts with humans, animals, and plants. Animals and plants, consumed by humans, are also calculated using DISPERSIA. Therefore, a program is needed that can represent the spatial distribution of radioactive materials in a polar grid following Gaussian distribution, which will then be overlaid with population, animal, and plant distribution maps according to the specific conditions of the area being studied. The spatial dose calculation is performed by multiplying the concentration with the Dose Conversion Factor. By configuring the program to follow the specific conditions of the analyzed area, this program can be easily applied to various regions with specific geospatial conditions. The capability to integrate with geospatial analysis tools and flexibility of choosing site location become the advantage of the DISPERSIA program.

The validation of the DISPERSIA BRIN was performed with the SIMPACT version 1.0 framework. This involves utilizing Excel-based tools and implementing programs written in Python to ensure accuracy and reliability in their analytical outputs. The case study demonstrates the application of the Dispersia-BRIN program for conducting radiological analysis at ULA site. Table 3 shows the validation of the program.

Python's syntax is easy to learn and read, making it an ideal choice for novice and experienced programmers. Moreover, Python boasts a rich library and framework ecosystem that enhances its functionality across various domains. For this research, several libraries were essential, including NumPy for numerical computations, Matplotlib for data visualization, and Pandas for data manipulation and analysis. Additionally, PyQt, QtWidgets, QtCore, and QtGui were utilized to create graphical user interfaces, while WinroseAxes was used to plot wind roses. The sklearn-model module from the scikit-learn library was employed for machine-learning tasks.

By leveraging Python's extensive libraries and its ability to connect with geospatial data, researchers can efficiently analyze and present complex spatial data. These libraries facilitate a better understanding of the nuclear facilities' geographic context and potential impact on their environment in terms of dose assessment

As a result, by understanding the dose status in a geospatial, researchers and authorities can predict critical information necessary for effective radiological safety and response planning. The dose status helps identify the location of the maximum radiation dose, which is crucial for pinpointing areas of highest exposure. It also determines the critical population groups at the most significant risk, enabling targeted protective measures. The analysis also defines the emergency planning zone, a designated area around the nuclear facility that requires specific emergency preparedness and response actions. Furthermore, it informs the design and implementation of an efficient monitoring system to continuously track radiation levels and ensure the safety of the environment and the public.

6. CONCLUSION

The Dispersia-BRIN program could be essential in an easy and rapid radiological analysis and emergency response planning. It uses various parameters like radionuclide type, wind speed, and direction to model how radioactive materials spread in the environment and estimate the radiation doses received by people and the ecosystem.

Dispersia-BRIN includes modules for handling source terms, meteorological data, population and environmental data, dispersion patterns, dose assessment, and geospatial visualization. These tools help researchers estimate the interaction between radioactive materials and living organisms, enabling them to identify high-dose areas, critical populations, and emergency planning zones.

Dispersia-BRIN effectively calculated and visualized the dispersion of radionuclides like Xe-133, I-131, and Cs-137 in a case study of a hypothetical NPP accident, helping to pinpoint areas with high radiation doses. The program's accuracy was validated against established tools like SIMPACT.

Using Python for its development, Dispersia-BRIN leverages powerful libraries and tools for data analysis, visualization, and geospatial mapping, making it user-friendly and versatile. This integration allows for effectively mapping and assessing nuclear facilities and their surroundings.

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3/7/2022. It is hoped that the outcomes of this research will significantly contribute to the advancement of the Radiological Environment Impact Assessment tool, supporting Indonesia's plan to establish safe and clean nuclear energy in the near future.

AUTHOR CONTRIBUTION

All of the authors are equally contributed as the main contributors of this paper. All authors read and approved the final version of the paper.

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