

Five-Year Environmental Radioactivity Monitoring around the Wolsong Nuclear Facilities Using Complementary Radiation Measurement Systems

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1. Introduction

Continuous surveillance of environmental radioactivity and the transparent disclosure of monitoring results are fundamental to radiological protection and to maintaining public confidence in communities hosting nuclear facilities. Long-term monitoring data are particularly valuable for characterizing site-specific baseline conditions and natural and anthropogenic variability. Such datasets provide an empirical basis for evaluating environmental radioactivity levels and identifying potential spatial or temporal patterns that may warrant further investigation. In South Korea, environmental radiological surveillance around nuclear facilities is conducted under a framework of national legislation, administrative guidelines, and local monitoring arrangements [1]. Within this framework, the Wolsong Nuclear Facility Environment & Safety Monitoring Committee, hereafter referred to as the Monitoring Organization, conducts routine radiological surveillance around the Wolsong Nuclear Power Plant and the low- and intermediate-level radioactive waste disposal facility, hereafter collectively referred to as the Wolsong nuclear facilities. The monitoring program covers a wide range of environmental matrices, including air, rainwater, surface soil, drinking water, surface water, groundwater, seawater, marine sediment, agricultural products, and marine biota. The resulting monitoring data are periodically disclosed to the public.

This study evaluated environmental radioactivity data collected by the Monitoring Organization from 2021 to 2025, with particular emphasis on the analytical coverage and environmental applicability of complementary radiation measurement systems. Radionuclide detection status and concentration ranges were evaluated according to environmental matrix and sampling location [2,3,4,5]. Results obtained at monitoring locations were descriptively compared with those from reference locations to identify indications of persistent or systematic spatial elevations potentially associated with facility operations. In addition, the suitability of the measurement approach for long-term environmental surveillance was considered based on the diversity and continuity of the analyses performed and compliance with applicable detection-limit requirements [1].

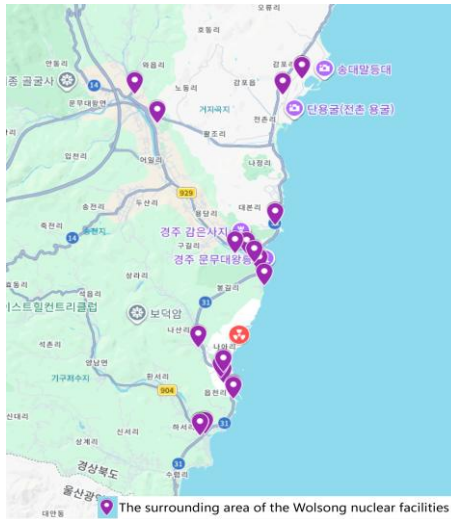
2. Materials and methods

2.1. Study Period, Environmental Sample Matrices, and Sampling Locations

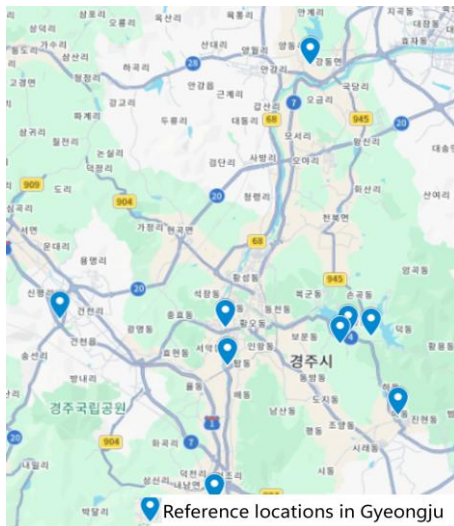
Environmental radioactivity data collected between January 2021 and December 2025 were included in this study [2,3,4]. The five-year period was selected to provide a sufficiently broad temporal basis for characterizing the range of routine environmental radioactivity levels while reducing the influence of isolated short-term fluctuations on the overall interpretation. Environmental samples were collected from representative monitoring and reference locations. Monitoring locations were selected to represent the major environmental and residential settings surrounding the Wolsong nuclear facilities. Reference locations were selected in areas expected to be minimally influenced by the operation of the facilities and were used to represent regional background conditions. For a clear representation of the spatial distribution of the sampling locations, the locations are presented in three separate maps in Figure 1: (a) monitoring locations within the Wolsong nuclear facilities, indicated by red markers, (b) monitoring locations in the surrounding area of the Wolsong nuclear facilities, indicated by purple markers, and (c) reference locations in Gyeongju, indicated by blue markers.



(a) Monitoring locations within the Wolsong nuclear facilities



(b) Monitoring locations in the surrounding area of the Wolsong nuclear facilities



(c) Reference locations in Gyeongju

Figure 1. Environmental sampling locations: (a) monitoring locations within the Wolsong nuclear facilities (red markers), (b) monitoring locations in the surrounding area of the Wolsong nuclear facilities (purple markers), and (c) reference locations in Gyeongju (blue markers).

2.2. Radiation Measurement Systems and Radioanalytical Methods

Environmental samples were analyzed using complementary radiation measurement systems and radionuclide-specific radioanalytical procedures. The measurement systems were selected according to the radiation type, target radionuclide, environmental matrix, and required analytical sensitivity. Gamma-emitting radionuclides were quantified by gamma-ray spectrometry using a High-Purity Germanium (HPGe) detector. Gross beta activity and ^{90}Sr were determined using a Low-Background alpha/beta counter. ^3H and ^{14}C were measured using a Liquid Scintillation Counter (LSC), whereas U and Pu isotopes were quantified using an alpha spectrometer. The method-specific detection limits achieved during routine measurements complied with the regulatory requirements stipulated in

Appendix 2 of the Regulations on Radiation Environmental Surveys and Assessment of Radiological Environmental Impact in the Vicinity of Nuclear Facilities. The complementary application of HPGe gamma-ray spectrometry, low-background alpha/beta counting, liquid scintillation counting, and alpha spectrometry enabled the measurement of gamma-, beta-, and alpha-emitting radionuclides across a broad range of environmental matrices.

2.3. Evaluation of Monitoring and Measurement Data

The five-year dataset was descriptively evaluated in terms of annual analytical throughput, radionuclide detection status, concentration ranges, environmental matrices, and sampling locations. Results below the applicable detection limits were retained and reported as values below the detection limit (e.g., <DL). Concentration ranges at monitoring and reference locations were descriptively compared to assess whether monitoring-location concentrations differed from or overlapped with those observed at reference locations. Where applicable, the monitoring results were also compared with concentration ranges reported in national environmental and marine radioactivity surveys [4, 5]. The applicability of the measurement framework to long-term environmental surveillance was considered based on the number and diversity of analyses performed, the ability of the analytical methods to quantify low-level environmental radioactivity, and compliance with regulatory detection-limit requirements.

3. Results and discussion

3.1. Analytical Coverage of the Radiation Measurement Program

The Monitoring Organization conducted 828 analyses in 2021, 841 in 2022, 1,027 in 2023, 966 in 2024, and 1,180 in 2025, resulting in a total of 4,842 analyses during the five-year study period. The sustained analytical coverage indicates the continued application of the complementary measurement systems to multiple environmental matrices and radionuclide groups throughout the study period. The integrated use of multiple measurement platforms allowed the monitoring program to address radionuclides with different decay characteristics and environmental behaviors. HPGe gamma-ray spectrometry was applied to gamma-emitting radionuclides, Low-Background alpha/beta counting to gross beta activity and ^{90}Sr , Liquid Scintillation Counting to beta-emitting radionuclides such as ^3H and ^{14}C , and alpha spectrometry to U and Pu isotopes.

3.2. Gamma-Ray Spectrometric Measurements

Artificial gamma-emitting radionuclides were generally below the applicable detection limits in most environmental samples. ^{131}I was below the detection limit at all sampling locations, and ^{60}Co was not

detected in the principal off-site environmental matrices. ^{137}Cs was quantified at low levels in selected marine products, seawater, and marine sediments. The ^{137}Cs concentrations in marine products ranged from less than 0.00842 to 0.119 Bq/kg-fresh. Concentrations in seawater ranged from 0.000928 to 0.00263 Bq/L, compared with 0.00104 to 0.00230 Bq/L at reference locations. In marine sediment, ^{137}Cs concentrations ranged from 0.439 to 0.726 Bq/kg-dry, whereas the corresponding range at reference locations was 0.300 to 0.902 Bq/kg-dry. The quantification of ^{137}Cs at low environmental levels demonstrates the importance of high-resolution gamma-ray spectrometry for the long-term surveillance of residual fallout radionuclides.

3.3. Low-Background Alpha/Beta Counting Measurements

Gross beta activity and ^{90}Sr were below the applicable detection limits in most samples. When detected, their concentrations remained low, and the descriptive comparison did not indicate a persistent spatial elevation at the monitoring locations. Gross beta activity ranged from 0.237 to 1.78 mBq/m³ in air, from less than 0.00948 to 0.211 Bq/L in rainwater, from 8.91 to 12.8 Bq/L in seawater, and from less than 0.0235 to 0.197 Bq/L in drinking water collected from water treatment plants. The ^{90}Sr concentrations ranged from less than 0.206 to 0.243 Bq/kg-dry in soil and from 0.260 to 0.269 Bq/L in groundwater. These results indicate that Low-Background alpha/beta counter provided analytical coverage for the routine surveillance of gross beta activity and chemically separated ^{90}Sr in environmental samples.

3.4. Liquid Scintillation Measurements

Among the radionuclides analyzed by liquid scintillation counting, ^3H was detected more frequently than most other artificial radionuclides. This finding highlights the importance of sensitive beta measurement techniques for environmental monitoring around nuclear facilities, particularly for radionuclides such as ^3H . ^3H concentrations in rainwater ranged from <1.94 to 58.2 Bq/L at monitoring locations, compared with 1.07 to 144 Bq/L at reference locations. In drinking water, concentrations ranged from 2.73 to 8.28 Bq/L at monitoring locations, compared with 1.14 to 11.9 Bq/L at reference locations. ^3H concentrations ranged from 4.52 to 16.3 Bq/L in groundwater. In seawater, concentrations ranged from 2.01 to 17.8 Bq/L at monitoring locations, compared with 1.12 to 36.5 Bq/L at reference locations. In drinking water collected from water treatment plants, ^3H concentrations were <2.09 Bq/L, while concentrations in surface water ranged from 2.03 to 5.25 Bq/L. In agricultural products represented by rice samples, ^3H concentrations were <2.28 Bq/kg-fresh. ^{14}C concentrations in groundwater ranged from 0.303 to 0.310 Bq/g-C, compared with 0.202 to 0.326 Bq/g-C at reference locations. In rice samples, the ^{14}C concentration was 0.258 Bq/kg-fresh.

Liquid scintillation counting therefore provided complementary analytical capability for beta-emitting radionuclides that cannot be adequately assessed using conventional gamma-ray spectrometry.

3.5. Alpha-Particle Spectrometric Measurements

Alpha spectrometry was applied to the determination of U and Pu isotopes in groundwater and surface soil. In groundwater, ^{235}U concentrations ranged from less than 0.0458 to 0.341 mBq/L, compared with less than 0.0212 to 0.507 mBq/L at reference locations. The corresponding concentration ranges for ^{234}U and ^{238}U were 0.168–6.82 mBq/L and less than 0.122–6.56 mBq/L, respectively. At the reference locations, the ranges were 0.101–13.6 mBq/L for ^{234}U and 0.0630–8.01 mBq/L for ^{238}U . In surface soil, concentrations ranged from 23.7 to 54.6 Bq/kg-dry for ^{234}U , from 1.60 to 3.49 Bq/kg-dry for ^{235}U , from 20.1 to 50.4 Bq/kg-dry for ^{238}U , and from less than 0.00688 to 0.0508 Bq/kg-dry for $^{239+240}\text{Pu}$. These ranges were comparable to those obtained at the reference locations. These results demonstrate the role of alpha spectrometry in providing isotope-specific information that cannot be obtained using gross alpha/beta counting alone.

3.6. Integrated Evaluation of the Measurement Framework

The complementary radiation measurement systems enabled the analysis of multiple radiation types and radionuclide groups across a broad range of environmental matrices. The achieved detection limits satisfied the applicable regulatory requirements, and the measurement systems were capable of quantifying low environmental levels of ^{137}Cs , ^3H , ^{14}C , U, and Pu isotopes where present. Although individual concentrations varied according to radionuclide, environmental matrix, and sampling location, descriptive comparisons between monitoring and reference locations, including those for ^3H in rainwater, drinking water, and seawater, did not indicate persistent or systematic spatial elevations at the monitoring locations. The measured concentration ranges were also broadly comparable with those reported in national environmental and marine radioactivity surveys.

4. Conclusion

A total of 4,842 environmental radioactivity analyses were conducted around the Wolsong Nuclear Power Plant and the low- and intermediate-level radioactive waste disposal facility between 2021 and 2025 using complementary radiation measurement systems. HPGe gamma-ray spectrometry, low-background alpha/beta counting, liquid scintillation counting, and alpha spectrometry collectively provided an integrated analytical framework for the determination of gamma-, beta-, and alpha-emitting radionuclides across diverse environmental matrices. The method-specific detection limits met the applicable regulatory requirements. Most artificial radionuclides

were below their respective detection limits in the majority of samples. Low-level ^{137}Cs activity was quantified in selected marine matrices, whereas ^3H was detected more frequently across water and agricultural samples. However, the descriptive comparison of monitoring and reference locations did not indicate consistent differences in concentration ranges, and the overall concentration ranges were broadly comparable with national background ranges. The results support the applicability of the complementary measurement framework to long-term environmental radioactivity surveillance around the Wolsong nuclear facilities. Continued application of the complementary measurement framework and accumulation of long-term monitoring data will support the reliability and continuity of environmental radioactivity surveillance.

REFERENCES

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