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A Study of the Content of Radionuclides in Coastal Seawater and Saline Groundwater in Jeju, Korea

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Abstract

This study investigated artificial radionuclides in coastal seawater and saline groundwater on Jeju Island, Korea, using samples collected during 2024. The ^{137}Cs concentration of coastal seawater samples ranged from 1.04 to 2.04 mBq kg⁻¹, with an average of 1.37 ± 0.27 mBq kg⁻¹. ^{60}Co and ^{131}I were below their respective detection limits in all coastal seawater samples. ^{137}Cs in saline groundwater was below the MDA at both investigated locations during all 2024 sampling periods. ^{90}Sr was below the MDA in both saline-groundwater samples collected in June 2024. ^3H was below the MDA in all saline-groundwater samples.

. Keywords

Jeju coastal seawater, saline groundwater, artificial radionuclides

Introduction

Artificial radionuclides released into the environment by atmospheric nuclear weapons testing, nuclear fuel reprocessing, and nuclear power plant accidents can persist in

terrestrial and marine environments for decades. Among these radionuclides, cesium-137 (^{137}Cs), strontium-90 (^{90}Sr), and tritium (^3H) are of particular interest because of their relatively long environmental persistence, different geochemical behaviors, and potential importance for environmental radioactivity assessment. ^{137}Cs has a physical half-life of approximately 30.17 years and is predominantly present in dissolved form in seawater, making it a useful tracer of water-mass transport and mixing [1–6]. ^{90}Sr has a half-life of approximately 28.8 years and exhibits chemical behavior similar to calcium, whereas ^3H , with a half-life of approximately 12.3 years, occurs predominantly as tritiated water and can therefore provide information on water movement and hydrological processes [7–11].

The marine environment has received substantial inputs of anthropogenic radionuclides from global fallout associated with atmospheric nuclear weapons testing. Historical datasets demonstrate that ^{137}Cs and ^{90}Sr became widely distributed throughout the global ocean following atmospheric testing during the 1950s and 1960s [1–4]. The distribution of these radionuclides is subsequently controlled by ocean circulation, vertical mixing, sediment interactions, radioactive decay, and other physical and biogeochemical processes. Because ^{137}Cs is relatively conservative in seawater, its concentration has frequently been used to investigate oceanic transport and water-mass dynamics [2–5].

The Fukushima Daiichi Nuclear Power Plant (FDNPP) accident in March 2011 resulted in an additional and substantial input of artificial radionuclides into the atmosphere and Pacific Ocean. The environmental behavior of FDNPP-derived radionuclides has subsequently been investigated extensively, particularly for ^{134}Cs and ^{137}Cs [12–17]. The releases resulted in detectable radiocesium throughout broad areas of the North Pacific, with subsequent transport governed by the Kuroshio Current, Kuroshio Extension, Oyashio Current, and large-scale circulation of the western North Pacific [12–15]. Reviews of the Fukushima accident have demonstrated that the fate of released radionuclides is determined by the interaction between source characteristics, ocean circulation, particle association, sedimentation, and biological processes [12, 16].

The Korean Peninsula is geographically located downstream of major oceanic circulation systems connecting the western North Pacific with the marginal seas surrounding Korea.

Consequently, monitoring of artificial radionuclides in Korean marine waters is important for establishing long-term environmental baselines. Earlier investigations reported measurable ^{134}Cs and ^{137}Cs in waters around the Korean Peninsula following the Fukushima accident. In July 2014, ^{137}Cs concentrations of approximately $1.6 \sim 1.9 \text{ mBq L}^{-1}$ were observed in southern Korean waters, together with low concentrations of ^{134}Cs , whereas ^{134}Cs was below detection limits in western Korean waters [17]. More recently, investigations of Korean marine environments have demonstrated that long-term ^{137}Cs , ^{90}Sr , and plutonium concentrations remain measurable at low environmental levels and that their distributions are related to regional oceanographic conditions [18]. Jeju Island is particularly important for environmental radioactivity monitoring because of its geographical position in the southern part of the Korean Peninsula and its close connection with the East China Sea and the Kuroshio-derived water system. Previous research demonstrated that Fukushima-derived ^{134}Cs and ^{137}Cs were deposited on Jeju Island following the 2011 accident, providing direct evidence that the island was affected by the atmospheric transport of radionuclides [19]. Therefore, the establishment of contemporary radioactivity baseline data for Jeju coastal waters is important for distinguishing long-term environmental background from possible future changes.

In addition to coastal seawater, saline groundwater is an important environmental compartment on Jeju Island. The island is composed predominantly of volcanic rocks and basaltic aquifers, and groundwater systems are strongly influenced by the geological structure, recharge processes, coastal hydrodynamics, and seawater–freshwater interactions [20–23]. Hydrogeochemical and isotopic investigations have demonstrated that seawater intrusion contributes to groundwater salinization in coastal areas of Jeju Island [20]. Tidal fluctuations can also influence the position of the fresh–saltwater interface and groundwater flow in coastal aquifers [21]. Thus, saline groundwater of seawater origin provides an important complementary matrix for evaluating the presence and behavior of anthropogenic radionuclides.

Previous research has extensively investigated radionuclides in seawater around the Korean Peninsula, but comparatively limited information is available concerning the simultaneous occurrence of ^{137}Cs , ^{90}Sr , and ^3H in saline groundwater on Jeju Island. This

is particularly relevant because these radionuclides differ substantially in their chemical and physical behaviors. ^{137}Cs can provide information about the occurrence and transport of radiocesium, ^{90}Sr provides an independent indicator of long-lived fission-product contamination, and ^3H is directly associated with the water molecule and may therefore provide complementary information on the origin and movement of saline groundwater [7–11].

The analytical determination of these radionuclides at environmental concentrations is challenging. Low-level ^{137}Cs measurements in seawater commonly require concentration procedures because environmental concentrations are generally close to or below the detection capability of direct gamma spectrometry. Ammonium phosphomolybdate (AMP) precipitation/adsorption has been widely applied to concentrate cesium from large seawater samples before gamma spectrometric measurement [24,25]. The AMP method has been demonstrated to provide high radiochemical recovery for low-level ^{137}Cs measurements in seawater [24]. Determination of ^{90}Sr is more complicated because ^{90}Sr is a pure beta emitter and therefore generally requires chemical separation before measurement. Radiochemical approaches based on separation of ^{90}Sr or its daughter ^{90}Y have been widely applied to environmental water samples [26–28]. Tritium analysis also requires careful sample preparation because environmental ^3H concentrations can be very low and other beta-emitting radionuclides may interfere with direct liquid scintillation measurements. Distillation is therefore frequently used to purify environmental water samples prior to liquid scintillation counting [29, 30]. The use of tritium as an environmental and hydrological tracer is well established, including in precipitation, groundwater, and marine environments [8–11, 31].

Recent research has further emphasized the importance of combining radionuclide measurements with hydrological information. Tritium concentrations in groundwater can provide information concerning recharge and groundwater residence time, whereas radiocesium measurements provide an independent indicator of anthropogenic radionuclide transport [22,23,31]. Such complementary measurements can be particularly valuable in a coastal volcanic island where seawater and groundwater interact.

The objective of the present study was therefore to establish baseline information on selected artificial radionuclides in coastal seawater and saline groundwater on Jeju Island. Coastal seawater samples collected from 10 locations in 2024 were analyzed for gamma-emitting radionuclides, with particular emphasis on ^{137}Cs . Saline groundwater samples were investigated for ^{137}Cs , ^{90}Sr , and ^3H . The study further evaluates the measured concentrations in relation to previously reported values from Korean coastal waters, the western North Pacific, and other marine environments.

Experimental

Sampling of Coastal Seawater and Saline Groundwater

Jeju Island is a volcanic island located south of the Korean Peninsula. Its hydrogeological system consists predominantly of basaltic volcanic formations containing highly permeable zones and complex groundwater flow pathways. Coastal groundwater systems are affected by interactions between meteoric recharge, groundwater discharge, and seawater intrusion [20–23]. The coastal location of Jeju also places the island within a region influenced by water masses originating from the East China Sea and the western North Pacific. Previous oceanographic and radioactivity studies have demonstrated the transport of radiocesium through these circulation systems [12–18].

The present study investigated two environmental compartments: coastal seawater and saline groundwater, referred to as lava seawater in the study dataset.

Coastal seawater samples were collected from 10 coastal locations around Jeju Island during 2024 (**Fig. 1**). The sampling locations were designated SW-1 to SW-10. More than 60 L of surface seawater sample was collected at each site; hydrochloric acid was added to prevent adsorption to the container walls or sedimentation before the samples were transported to the laboratory. The collected seawater samples underwent a filtration process prior to gamma-ray spectroscopic analysis.

Saline groundwater samples were collected from locations (in Jeju Lava Seawater Industrial Complex) utilized for industrial purposes. Two sampling locations were designated LW-1 and LW-2.

For ^{137}Cs and ^3H , samples were collected repeatedly throughout 2024; sampling was conducted once each in February, April, June, August, and October. A sample for ^{90}Sr was collected once in June 2024.

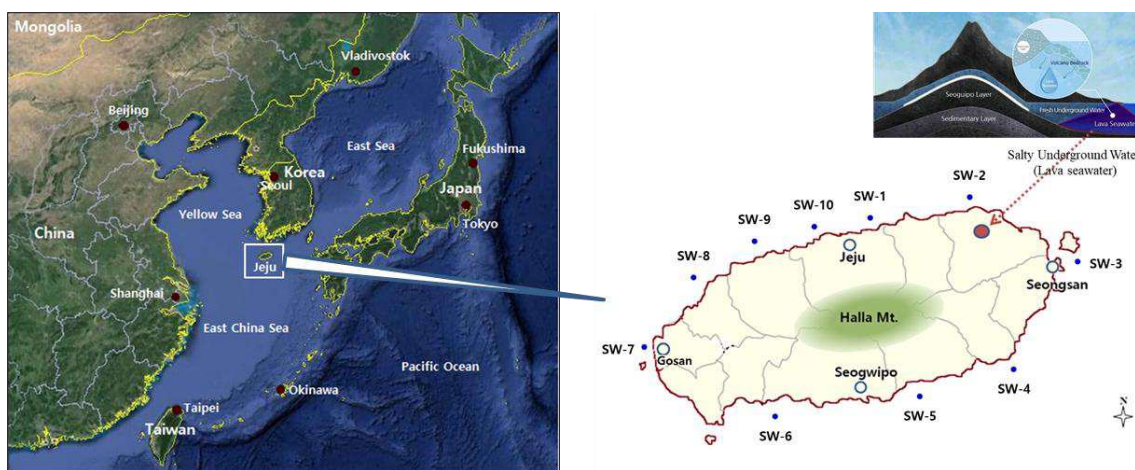


Fig. 1 Location of sampling site of radionuclides in coastal seawater and saline groundwater.

Gamma-emitting radionuclide analysis

For the analysis of ^{40}K , ^{60}Co , and ^{131}I , a 1.0 kg filtered seawater sample is collected, placed in a 1 L Marinelli beaker, and were measured using a high-purity Germanium (HPGe) detector for 80,000 seconds.

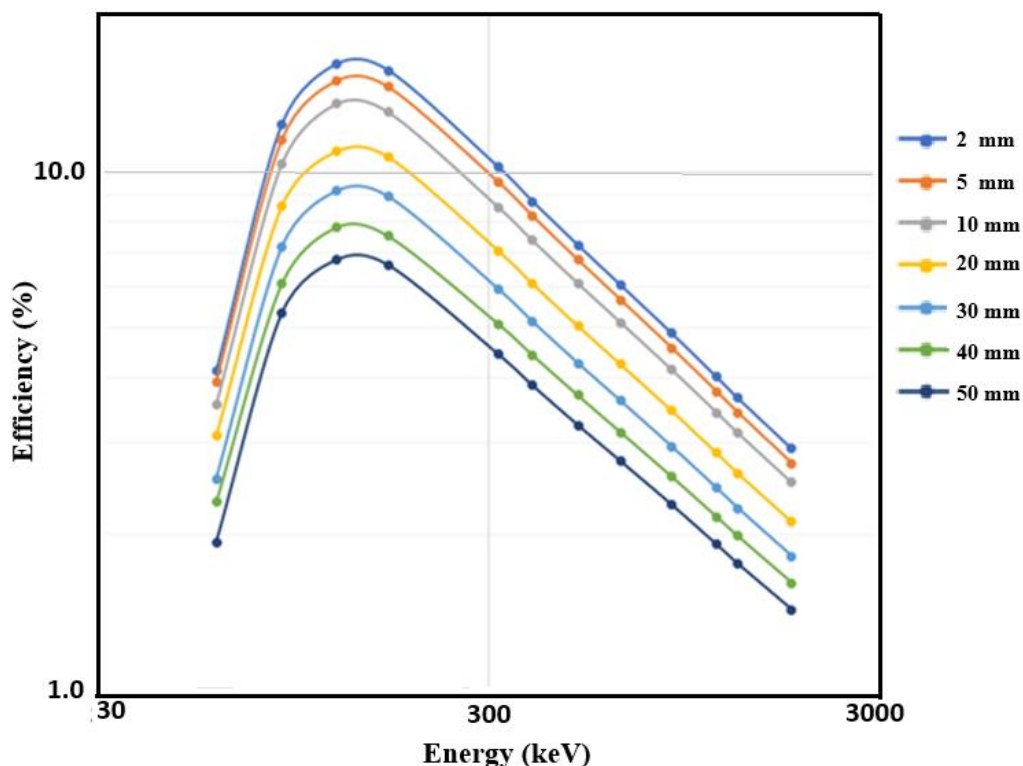
The analysis of ^{137}Cs in seawater and saline groundwater was performed using the ammonium molybdophosphate (AMP) co-precipitation method. The AMP co-precipitation method is an established technique for the quantitative analysis of low-level radioactive cesium in seawater. Aoyama et al. demonstrated that applying the AMP method to large-volume seawater samples yields high chemical and radiochemical recovery rates [24]. This

method exploits the strong affinity of AMP for cesium, enabling quantification via gamma-ray spectrometry following co-precipitation

For the analysis of ^{137}Cs , 60.0 L of filtered seawater and saline groundwater were placed into a reaction vessel. After adding 30.0 g of AMP, the mixture was stirred, and the pH was adjusted to 1.5–2.0 using HCl. The mixture was stirred for one hour to ensure thorough mixing. After allowing the mixture to stand for at least 24 hours. The supernatant was removed, and the precipitated AMP was recovered using filter paper (GF/C, Cat. No. 1822-047). The residue was eluted three times with deionized water and then dried at 110°C for two hours in an oven. After accurately weighing the dried sample and calculating the recovery rate, the sample was placed in a U8 vial (50 mm diameter, 70 mm height; Mizuho Chemical Co., Japan) and measured using an HPGe detector for 80,000 seconds.

The measurement system used for precision gamma-nuclide analysis consisted of a HPGe detector and a multichannel analyzer (GEM30P4-76-SMP, AMETEK ORTEC; 30% relative efficiency, p-type). The analysis targeted gamma-emitting nuclides with energies ranging from approximately 40 keV to 3,000 keV. Consequently, energy and peak efficiency calibrations were performed using a mixed gamma-calibration standard volume source (241PB20-15, KRISS) containing nuclides that emit gamma rays between 50 keV and 2,000 keV (specifically: ^{241}Am , ^{109}Cd , ^{57}Co , ^{139}Ce , ^{51}Cr , ^{113}Sn , ^{85}Sr , ^{137}Cs , ^{88}Y , and ^{60}Co). To prepare the measurement standards, the mixed gamma-emitting standard volume source was appropriately diluted with a 1 M HCl solution; the solution was then weighed in a U8 vial (the measurement sample container), and its radioactivity concentration was calculated. Since it is difficult to ensure a uniform fill height for environmental samples, seven standard volume sources were prepared using 1M HCl solution at height intervals of approximately 5 mm ranging from 2 mm to 50 mm to obtain spectra and perform calculations for efficiency and energy calibration. Additionally, the mass of each source was accurately determined to allow for density correction regarding the self-absorption effect. Using Genie 2000 (Canberra Co.) software, interpolation formulas relating gamma-ray energy and height were derived to establish calibration spectra - incorporating efficiency, energy calibration equations, and resolution - at intervals ranging from 2 mm and 5 mm up to 50 mm. The ^{60}Co and ^{88}Y radionuclides present in the standard volumetric sources exhibit a "coincidence summing effect"—where the simultaneous emission of gamma rays (1173.23 keV and 1332.5 keV for ^{60}Co ; 898.04 keV and 1836.06 keV for ^{88}Y) alongside other gamma rays (2505.74 keV and 2734.1 keV) reduces detection efficiency. Additionally, differences in apparent density between the standard source and the sample can lead

185 to reduced detection efficiency due to the self-absorption effect caused by interactions between the
 186 sample material and gamma rays. Consequently, the reductions in detection efficiency caused by
 187 the coincidence summing effect and the self-absorption effect were corrected in accordance with
 188 the efficiency calibration procedure (**Fig 2**).



189

190 **Fig. 2** HPGe efficiency by U8 vial height using a standard source.

191 The pre-treated samples were measured using a gamma spectrometer (comprising a HPGe detector
 192 and a multichannel analyzer) with a background radiation measurement time of 100,000 seconds
 193 and a sample measurement time of 80,000 seconds. The measured spectra were analyzed to identify
 194 gamma-emitting radionuclides in the samples using analysis software (Genie 2000, Canberra Co.)
 195 and applying calibrations for energy resolution and efficiency.

196 **Determination of ^{90}Sr in saline groundwater**

197 Because ^{90}Sr is a pure beta emitter, chemical purification is required to minimize matrix
 198 effects and interfering radionuclides. Conventional ^{90}Sr procedures commonly involve
 199 separation of Sr or its daughter ^{90}Y followed by beta counting or another appropriate

measurement technique [26–28]. For precipitation (such as rainwater), methods involving concentration via ion-exchange resin adsorption or water evaporation are used. However, since seawater contains high concentrations of various salts (Na, Mg, Cl, etc.), a carbonate precipitation step is employed to recover the precipitate and remove these abundant ions. The ^{90}Sr concentration in saline groundwater was determined following chemical pretreatment with fuming nitric acid (**Fig. 3**).

As ^{90}Sr exists in seawater (saline groundwater) at extremely low concentrations—similar to other radionuclides—a large volume of seawater is required for accurate quantification. Oxalic acid and NaOH were added to a 60 L saline groundwater sample to induce the precipitation of strontium (calcium) oxalate ($\text{Sr}(\text{Ca})\text{C}_2\text{O}_4$) at pH 4.2. After recovering the precipitate, fuming nitric acid was added to remove calcium by exploiting the difference in solubility between calcium and strontium in 70% nitric acid. Residual radium, barium, and lead in the strontium solution were removed via barium chromate co-precipitation. Subsequently, following carbonate and iron precipitation steps, an SrCO_3 precipitate was obtained using a saturated ammonium carbonate solution; this was filtered and dried to determine the recovery rate. The recovery rate was calculated by measuring the sample before and after pretreatment using inductively coupled plasma-optical emission spectrometer (ICP-OES, AVIO 550). The SrCO_3 precipitate was dissolved in a small amount of HCl (1:3), and a 10 mL aliquot of the filtrate was set aside for 14 days to reach radioactive equilibrium before measurement via LSC (Quantulus 1220, Wallace) using the Cherenkov counting method. To determine the ^{90}Sr efficiency, the ^{90}Y counting efficiency is calculated by measuring the Cherenkov light of ^{90}Y in a ^{90}Sr standard sample using a liquid scintillation counter. Seawater samples were placed in the liquid scintillation counter and measured for 200 minutes.

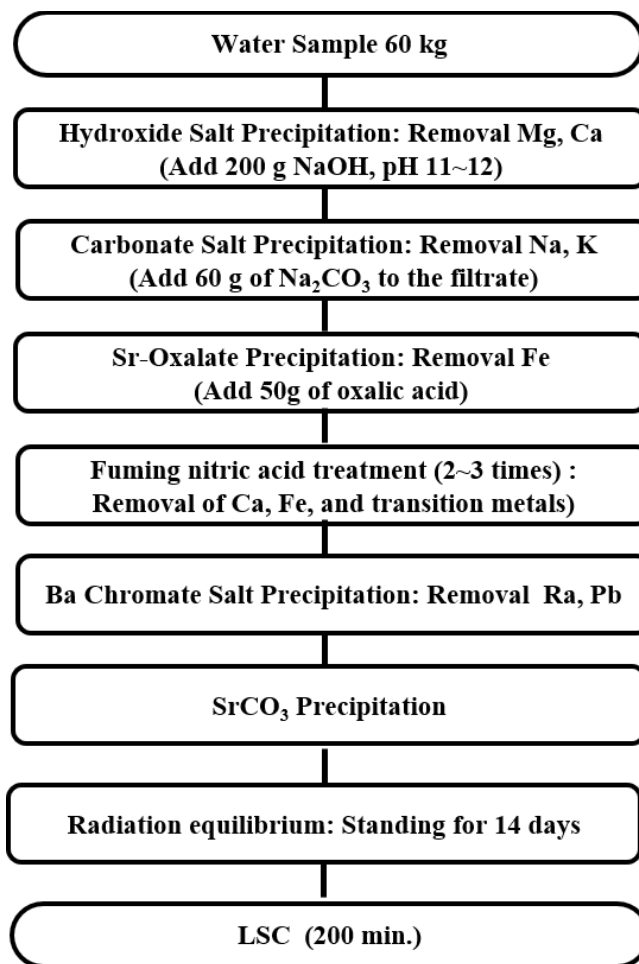


Fig. 3 The flowchart of procedure for isotopic analysis of ^{90}Sr saline groundwater.

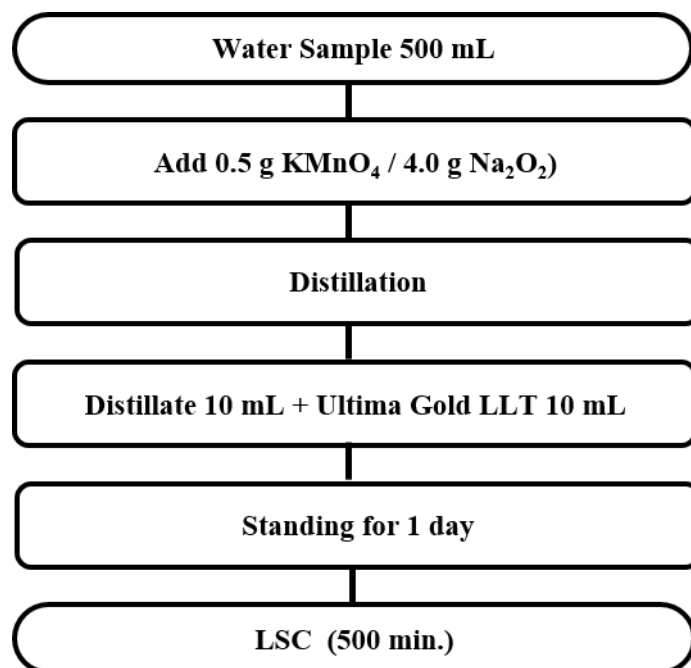
The estimates employ Currie's equation for minimum detectable activity (MDA), given in Equation (1) [32], where C_b , T_b , E , V_s , and T_s are the background count rate (cpm), the background count time (min), the counting efficiency, the sample weight (grams), and the sample count time (min).

$$\text{MDA} = \frac{2.71 + 4.65 \sqrt{C_b T_b}}{E \times V_s \times T_s \times 60} \quad (1)$$

Determination of ^3H in saline groundwater

Distillation is commonly employed for environmental tritium analysis because it removes non-volatile constituents and potential interfering radionuclides prior to liquid scintillation

234 counting [29, 30]. Tritium in saline groundwater was analyzed after simple distillation (Fig.
235 4).



236

237 **Fig. 4** The flowchart of procedure for isotopic analysis of tritium in saline groundwater.

238 A 500 mL sample of lava seawater was transferred to a distillation flask (a three-necked
239 round-bottom flask) connected to a distillation apparatus. A small amount of KMnO₄ was
240 added, and the sample was distilled; AgNO₃ solution was then added dropwise to the
241 distillate to check for the presence of Cl⁻ ions. This distillation process was repeated until
242 no Cl⁻ ions were detected in the distillate. Approximately 4.0 g of Na₂O₂ powder was added
243 to 400 mL of the distilled solution to induce co-precipitation; the supernatant was then
244 collected and distilled again. After discarding the first 50 mL of the distillate, a 10 mL
245 aliquot was placed in a 20 mL LSC vial, mixed thoroughly with 10 mL of Ultima Gold
246 LLT Scintillator, and stored for one day in a cool, dark place within the counting instrument.

247 Using a LSC (Quantulus 1220, Wallace), a quenching curve spectrum was obtained and
248 counting efficiency was determined by measuring ten samples prepared by adding water
249 to a ³H standard (NIST 4927g).

The minimum detectable activity (MDA) was calculated according to the statistical approach proposed by employ Currie's equation [32].

Results and discussion

Gamma-emitting radionuclides in coastal seawater

The gamma-spectrometric results for the 10 coastal seawater samples are summarized in **Table 1**. The ^{137}Cs concentrations ranged from 1.04 to 2.04 mBq kg^{-1} , with an arithmetic mean of $1.37 \pm 0.27 \text{ mBq kg}^{-1}$. The maximum concentration occurred at SW-8 ($2.04 \pm 0.27 \text{ mBq kg}^{-1}$), whereas the minimum occurred at SW-5 ($1.04 \pm 0.12 \text{ mBq kg}^{-1}$). The ten-site dataset therefore exhibited approximately a two-fold difference between the minimum and maximum concentrations.

The detection of ^{137}Cs at all 10 coastal seawater locations is consistent with the persistence of anthropogenic radiocesium in the marine environment. Global monitoring studies have shown that measurable ^{137}Cs remains in ocean surface waters decades after the major atmospheric nuclear testing period [1–5]. ^{137}Cs is predominantly dissolved in seawater and is consequently transported efficiently with water masses [3–6].

The magnitude of the concentrations measured in the present study is also broadly comparable with contemporary observations in Korean waters. A 2024 survey of the East Sea and coastal waters off southern Korea reported surface ^{137}Cs concentrations of 0.88~1.55 mBq kg^{-1} in the East Sea and 1.38~2.24 mBq kg^{-1} in southern Korean waters [34]. The Jeju mean concentration of $1.37 \pm 0.27 \text{ mBq kg}^{-1}$ therefore falls within the range reported for neighboring Korean marine environments.

Table 1 Gamma-emitting radionuclides in coastal seawater around Jeju Island in 2024

Samples	^{40}K (Bq kg^{-1})	^{60}Co (Bq kg^{-1})	^{131}I (Bq kg^{-1})	^{137}Cs (mBq kg^{-1})
SW-1	7.11 ± 1.41	<0.58	<2.05	1.17 ± 0.11
SW-2	12.6 ± 1.65	<0.62	<0.52	1.45 ± 0.12

SW-3	8.10 ± 1.40	<0.57	<0.51	1.29 ± 0.14
SW-4	11.7 ± 1.80	<0.60	<0.58	1.31 ± 0.15
SW-5	9.80 ± 1.70	<0.60	<0.59	1.04 ± 0.12
SW-6	16.1 ± 1.64	<0.42	<0.44	1.57 ± 0.14
SW-7	9.40 ± 1.50	<0.52	<0.49	1.14 ± 0.13
SW-8	12.0 ± 1.70	<0.66	<0.55	2.04 ± 0.27
SW-9	10.4 ± 1.53	<0.47	<1.33	1.47 ± 0.20
SW-10	11.1 ± 1.63	<0.47	<0.41	1.27 ± 0.21
Mean	10.8 ± 2.40	ND	ND	1.37 ± 0.27

ND: not detected; <: below the minimum detectable activity.

A previous investigation of waters surrounding the Korean Peninsula in July 2014 reported ^{137}Cs concentrations of approximately $1.6\text{--}1.9\text{ mBq L}^{-1}$ in southern Korean waters and detected low levels of ^{134}Cs , suggesting a contribution from FDNPP-derived radiocesium transported by Kuroshio-derived water [17]. The persistence of ^{137}Cs in the present 2024 Jeju dataset should, however, not be interpreted as direct evidence of a new Fukushima-derived input. Because ^{137}Cs has a long half-life and multiple historical sources, including global fallout and the Fukushima accident, concentration measurements of ^{137}Cs alone cannot uniquely identify its source.

The absence of detectable ^{60}Co and ^{131}I at all sampling locations is also noteworthy. ^{131}I has a short physical half-life of approximately eight days and therefore cannot persist in the environment over long periods following its original release. Similarly, ^{60}Co is not expected to provide the same long-term environmental signal as ^{137}Cs . The lack of detectable ^{131}I is therefore consistent with the absence of a strong recent source at the time of sampling.

The measured ^{40}K concentrations ranged from 7.11 to 16.1 Bq kg^{-1} , with an average of $10.8 \pm 2.4\text{ Bq kg}^{-1}$. Unlike ^{137}Cs , ^{40}K is a naturally occurring radionuclide associated with the natural potassium content of seawater. Its presence in all samples provides a useful indication of the natural radioactive component of the seawater matrix.

The spatial variation of ^{137}Cs among the 10 sampling locations was relatively limited compared with the large differences that can occur following a localized radioactive release. Concentrations were between 1.04 and 2.04 mBq kg^{-1} , while the mean was 1.37 mBq kg^{-1} .

The coefficient of variation calculated from the reported mean and standard deviation was approximately 20%. This indicates measurable spatial variability but does not by itself demonstrate a specific source or transport mechanism.

Several mechanisms could contribute to the observed variability. These include differences in local water exchange, coastal currents, freshwater influence, sampling conditions, and the spatial distribution of radiocesium in the surrounding marine environment. The relatively conservative behavior of ^{137}Cs means that local concentrations may also reflect the history of the water mass rather than only recent local inputs [3,5,6].

Previous studies have demonstrated that radionuclide concentrations around the Korean Peninsula are affected by the mixing of Kuroshio-derived water and continental shelf waters [17].

^{137}Cs in Jeju saline groundwater

The ^{137}Cs concentrations measured in saline groundwater are presented in **Table 2**. All ^{137}Cs measurements in saline groundwater were below the corresponding MDA, with reported MDA values ranging from <0.49 to $<0.78 \text{ mBq kg}^{-1}$.

This finding is important because the saline groundwater is considered to have a seawater origin. The presence of seawater-derived water does not necessarily imply that the radionuclide concentrations in the groundwater will be identical to those in contemporary coastal seawater. During groundwater recharge, transport, and residence, radionuclides can undergo dilution, mixing, sorption, and other processes. The low ^{137}Cs concentrations are consistent with the possibility that saline groundwater represents a mixture of seawater and groundwater with a substantially different radionuclide inventory. Previous hydrogeochemical studies of Jeju demonstrated that coastal saline groundwater can result from seawater intrusion and mixing processes [20, 21].

318 **Table 2** ^{137}Cs activity concentration in Jeju saline groundwater

Sampling site	Sampling date	^{137}Cs (mBq kg ⁻¹)
LW-1	24.02.28	<0.63
	24.04.26	<0.73
	24.06.13	<0.54
	24.08.29	<0.53
	24.10.16	<0.49
LW-2	24.02.28	<0.63
	24.04.26	<0.78
	24.06.13	<0.57
	24.08.29	<0.53
	24.10.16	<0.50

319 <: below the minimum detectable activity.

320 The AMP concentration method is particularly relevant to the interpretation of these low
 321 values. Because AMP methods have been developed specifically for low-level radiocesium
 322 measurements, the use of an adsorption/concentration procedure provides an analytical
 323 advantage over direct measurement when concentrations approach the environmental
 324 detection limit [24,25]. The absence of detectable ^{137}Cs should nevertheless be expressed
 325 as a measurement result below MDA rather than as proof that ^{137}Cs is completely absent.
 326 The distinction is important for environmental radioactivity studies. The present data
 327 demonstrate that ^{137}Cs concentrations were below the detection capability of the
 328 analytical procedure used.

329 ^{90}Sr in Jeju saline groundwater

330 The ^{90}Sr results are summarized in Table 3. All ^{90}Sr measurements in saline groundwater
 331 were below the corresponding MDA, with reported MDA values ranging from <0.33 to
 332 <0.39 mBq kg⁻¹. The low ^{90}Sr results are consistent with the generally low concentrations
 333 observed in contemporary marine environments away from direct sources. Global marine
 334 datasets have demonstrated substantial declines in ^{90}Sr since the period of maximum
 335 atmospheric nuclear testing, although residual ^{90}Sr remains measurable in ocean waters
 336 [1,4]. For comparison, a recent study of seawater southeast of Jeju Island measured ^{90}Sr

activities of 0.57–1.0 Bq m⁻³ during November 2021~January 2023, with no distinct temporal or spatial trend [34]. These concentrations correspond to approximately 0.57–1.0 mBq L⁻¹. The sub-MDA saline-groundwater results in the present study are therefore lower than or comparable with the concentrations observed in open coastal seawater, although direct quantitative comparison should be made cautiously because the matrices, sampling locations, units, and analytical methods differ.

The difference between seawater and saline groundwater may reflect mixing with low-activity groundwater, dilution, residence time, and radionuclide transport behavior. Because Sr behaves more conservatively than Cs with respect to some mineral surfaces and is chemically analogous to Ca, its groundwater behavior can differ substantially from that of Cs [26~28].

Table 3 ⁹⁰Sr activity concentration in Jeju saline groundwater

Sampling site	Sampling date	⁹⁰ Sr (mBq kg ⁻¹)
LW-1	24.06.21	<0.63
LW-2	24.06.21	<0.73

<: below the minimum detectable activity.

³H in Jeju saline groundwater

The ³H results are shown in Table 4. All ³H concentrations were below the MDA, with detection limits ranging from <1.64 to <2.27 Bq L⁻¹. Tritium is particularly useful in groundwater investigations because it is incorporated into the water molecule as HTO and therefore provides information complementary to particle-reactive or ion-exchange-sensitive radionuclides. Environmental tritium has been widely used to characterize groundwater recharge and residence times [8–11,31]. Long-term observations in Korea demonstrate that tritium concentrations in precipitation vary seasonally and spatially. Chae and Kim reported maximum concentrations in spring and minimum concentrations in summer, with lower values at coastal stations owing partly to marine moisture influence [10]. Earlier Korean measurements also demonstrated spatial variations in precipitation, groundwater, and seawater tritium concentrations [31]. The absence of detectable ³H in the

present saline-groundwater samples should not be interpreted as evidence of an absence of water exchange with the ocean. Rather, it indicates that any ^3H concentration was below the analytical detection capability under the measurement conditions employed. The relatively low MDA values achieved in the present study are useful for establishing a baseline for future monitoring. If a future sample produces a measurable ^3H concentration above the established MDA, comparison with the present dataset could provide evidence for temporal changes.

Table 4 ^3H activity concentration in Jeju saline groundwater

Sampling site	Sampling date	^3H (Bq L ⁻¹)
LW-1	24.02.28	<2.14
	24.04.26	<2.17
	24.06.13	<1.64
	24.08.29	<2.23
	24.10.16	<2.24
LW-2	24.02.28	<2.16
	24.04.26	<2.22
	24.06.13	<1.65
	24.08.29	<2.27
	24.10.16	<2.27

<: below the minimum detectable activity.

Comparison with previous studies

Table 5 summarizes representative published measurements relevant to the present study. The ^{137}Cs concentration range observed in Jeju coastal seawater is consistent with the magnitude of contemporary ^{137}Cs concentrations reported for neighboring Korean marine waters. The agreement is particularly notable because the present samples were collected from coastal locations around Jeju rather than from offshore deep-water stations.

Table 5 Representative literature data for artificial radionuclides in environments

Region	Radionuclide	Representative result	Study
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Pacific/Indian Oceans	^{90}Sr , ^{137}Cs , Pu	2000 surface-water ^{137}Cs generally $0.1\text{--}2.8\text{ mBq L}^{-1}$	[4]
Western North Pacific	^{137}Cs	Deep-water concentrations $<0.1\text{ Bq m}^{-3}$ in 1997–1998	[24]
South Pacific	^{137}Cs , Pu	^{137}Cs $0.07\text{--}1.7\text{ Bq m}^{-3}$	[5]
North Pacific	^{137}Cs	Subsurface ^{137}Cs maxima related to water masses	[6]
North Pacific	^{134}Cs , ^{137}Cs	Fukushima-derived radionuclide transport	[12]
Global ocean	^{137}Cs	Modelled Fukushima transport	[14]
South Korea	^{137}Cs , ^{90}Sr , Pu	Long-term monitoring, 2011–2020	[18]
Korean Peninsula	^{134}Cs , ^{137}Cs	^{137}Cs $1.6\text{--}1.9\text{ mBq L}^{-1}$ in southern waters	[17]
Jeju Island	^{134}Cs , ^{137}Cs	Fukushima-derived radiocesium detected in soils/rain	[19]
Southeast of Jeju	^{90}Sr	$0.57\text{--}1.0\text{ Bq m}^{-3}$	[34]
Jeju coastal seawater	^{137}Cs	$1.04\text{--}2.04\text{ mBq kg}^{-1}$; mean $1.37 \pm 0.27\text{ mBq kg}^{-1}$	Present
Jeju saline groundwater	^{137}Cs	$<0.49\text{--}<0.78\text{ mBq kg}^{-1}$	Present
Jeju saline groundwater	^{90}Sr	$<0.33\text{--}<0.39\text{ mBq kg}^{-1}$	Present
Jeju saline groundwater	^3H	$<1.64\text{--}<2.27\text{ Bq L}^{-1}$	Present

378

379 The 2024 Korean marine survey reported ^{137}Cs concentrations of $0.88\text{--}1.55\text{ mBq kg}^{-1}$ in
380 East Sea surface waters and $1.38\text{--}2.24\text{ mBq kg}^{-1}$ in southern Korean coastal waters [33].
381 The present mean of 1.37 mBq kg^{-1} lies between these regional ranges. This consistency
382 supports the interpretation that the Jeju coastal measurements represent the same general
383 low-level marine radiocesium environment observed around the southern Korean
384 Peninsula.

385 Nevertheless, concentration similarity does not establish a common source. Contemporary
386 ^{137}Cs in Korean waters can reflect the combined influence of historical global fallout,
387 residual Fukushima-derived material, ocean circulation, and other minor sources. Source
388 attribution would require additional radionuclides, isotopic ratios, time-series
389 measurements, and oceanographic information.

The establishment of a site-specific baseline is particularly important for Jeju because previous studies have demonstrated that the island has received measurable Fukushima-derived radionuclides through atmospheric deposition [19]. At the same time, the present results show that current coastal seawater contains low but measurable ^{137}Cs concentrations, while ^{137}Cs , ^{90}Sr , and ^3H in the investigated saline groundwater were below the respective detection limits. These observations provide complementary baseline information for future monitoring.

Conclusions

This study investigated artificial radionuclides in coastal seawater and saline groundwater on Jeju Island, Korea, using samples collected during 2024.

Ten coastal seawater locations were investigated by gamma spectrometry, while saline groundwater was analyzed for ^{137}Cs , ^{90}Sr , and ^3H . ^{137}Cs was detected in all 10 coastal seawater samples. The concentration ranged from 1.04 to 2.04 mBq kg^{-1} , with an average of $1.37 \pm 0.27 \text{ mBq kg}^{-1}$. The values were within the range of contemporary ^{137}Cs concentrations reported for neighboring Korean marine waters. ^{60}Co and ^{131}I were below their respective detection limits in all coastal seawater samples. The absence of detectable ^{131}I is consistent with its relatively short half-life and the lack of evidence for a strong recent input during the sampling period.

^{137}Cs in saline groundwater was below the MDA at both investigated locations during all 2024 sampling periods. The reported MDA range was $<0.49 \sim <0.78 \text{ mBq kg}^{-1}$. ^{90}Sr was below the MDA in both saline-groundwater samples collected in June 2024. The reported limits were <0.33 and $<0.39 \text{ mBq kg}^{-1}$. The estimated activities of $0.113 \sim 0.168 \text{ mBq kg}^{-1}$ remained below the respective detection limits and therefore should not be interpreted as confirmed detections. ^3H was below the MDA in all saline-groundwater samples. The reported MDA range was $<1.64 \sim <2.27 \text{ Bq L}^{-1}$.

The difference between detectable ^{137}Cs in coastal seawater and non-detectable ^{137}Cs , ^{90}Sr , and ^3H in saline groundwater indicates that radionuclide concentrations cannot be assumed to be identical between seawater and saline groundwater, even where seawater intrusion contributes to groundwater salinity

The results of this study establish a 2024 baseline for radionuclides in coastal seawater and saline groundwater off Jeju Island. Future research aims to integrate radionuclide measurements with data on salinity, major ions, stable isotopes, groundwater age tracers, and oceanographic conditions, alongside repeated seasonal sampling. This multifaceted approach will contribute to a better understanding of the relationships between coastal seawater, saline groundwater, and the transport of anthropogenic radionuclides. Overall, this dataset demonstrates the value of systematic radionuclide monitoring in the coastal environment of Jeju. The quantitative ^{137}Cs data for coastal seawater and the detection limit information obtained for ^{137}Cs , ^{90}Sr , and ^3H in saline groundwater will serve as a foundation for building a long-term database on environmental radioactivity in the region.

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Conflict of interest

The authors declare that they have no conflict of interest.

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