Article

Integrated and Portable Probe Based on Functional Plastic Scintillator for Detection of Radioactive Cesium

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Abstract: The highly reliable and direct detection of radioactive cesium has gained potential interest due to in-situ detection and monitoring in environments. In this study, we elucidated an integrated and portable probe based on functional plastic scintillator for detection of radioactive cesium. A functional plastic scintillator with improved detection efficiency was fabricated including CdTe (cadmium telluride) material. Monolith-typed functional plastic scintillator having a diameter of 50 mm and a thickness of 30 mm was manufactured by adding 2,5-diphenyloxazole (PPO, 0.4 wt%), 1,4-di[2-(5phenyloxazolyl)]benzene (POPOP, 0.01 wt%), and CdTe (0.2 wt%) materials in a styrene-based matrix. To evaluate the applicability of the plastic scintillator manufactured to in-situ radiological measurement, an integrated plastic detection system was created, and the measurement experiment was performed using the Cs-137 radiation source. Additionally, detection efficiency was compared with a commercial plastic scintillator. As results, the efficiency and light yield of a functional plastic scintillator including CdTe were higher than a commercial plastic scintillator. Furthermore, the remarkable performance of the functional plastic scintillator was confirmed through comparative analysis with Monte Carlo simulation.

Keywords: detection; integrated portable probe; Cs-137; plastic scintillator; simulation

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1. Introduction

In general, it is necessary to develop residual radioactivity measurement technology that can easily access the site, and the technology in radiological measurements that can safely and effectively evaluate the environment, contaminated by a nuclear safeguard or serious accident at a nuclear facility [1–7]. In addition, there must be verified that the site is not contaminated for reuse of the site after the nuclear facilities are dismantled. Until now, a lot of studies have been conducted to secure technologies that can prepare for serious accidents such as Chernobyl and Fukushima [7–13]. The total amount of radioactivity emitted by the Chernobyl accident was about 12×10^{18} Bq [14]. The behavior of radioactive particles largely depends on diffusion factor, particle size, and rainfall, and large particles such as nuclear fuel dust were mostly deposited within 100 km radius of the reactor [13]. In the Chernobyl nuclear accident, radioactive Cs-137 from one of the fission products of U-235 contaminated about 125,000 km² in Belarus, Ukraine, and Western Russia with a concentration of 37 kBq/m² [13]. In the Fukushima accident, a large area was contaminated by the radioactive elements, and one of the major contaminated radionuclides was analyzed as a Cs-137 [12,13]. Additionally, Cs-137 was easily released from the nuclear power plant accident and was rapidly spread to the environments as a mobile element. The decay diagram and probability of Cs-137 were shown in Figure 1 and Table 1. Most of Cs-137 decays to Ba-137 and then gamma decays to a stable state at 0.662 MeV. There are two β^- decay channels. First, 94.6% of β^- decays proceed from Cs-137 to the excited state

of Ba-137m with maximum electron energy of 0.514 MeV. The Ba-137m is a metastable state that decays with a 2.552 min half-life to the ground state of Ba-137 with emission of a 0.662 MeV gamma ray photon. Second, 5.4% of β^- decay proceeds directly from Cs-137 to the ground state of Ba-137 with maximum electron energy of 1.176 MeV. Cs-137 has a half-life of 30.17 ± 0.03 years [15], which can cause long-term damage when exposed to the environment [16–25]. Cesium has similar chemical properties to potassium (K), so it is easily concentrated in crops such as rice. In addition, it occupies a large amount of artificial radioactive gamma-emitting isotopes that have been leaked through nuclear tests and nuclear accidents. In this regard, cesium is an important radionuclide for detection and monitoring in environments and contaminated sites.

Figure 1. Decay diagram of ^{137}Cs .

Table 1. β^- decay process, electron energy, and probability of Cs-137.

	^{137}Cs	$(E_k)_{\text{max}}$	$(E_k)_{\text{avg}}$	(E_γ)	Probability
①	β^- decay	0.514 MeV	0.170 MeV	-	94.6%
②	β^- decay	1.176 MeV	0.420 MeV	-	5.4%
③	Internal conversion (K shell)	-	-	-	7.8%
	Internal conversion (L, M shell)	-	-	-	1.80%
④	γ decay	-	-	0.662 MeV	85%

Plastic detectors are widely used as large size detectors. Additionally, over the past few decades, many studies have been conducted on plastic scintillators composed of polymer matrix containing nanomaterials as an alternative to conventional inorganic scintillators [26]. Plastic scintillators are generally manufactured by thermal polymerization, doping, or coating by adding materials such as fluorescent dye. However, direct mixing of nanomaterials and polymers is less efficient in producing transparent nanocomposites. Because nanomaterials tend to aggregate due to their high specific surface area and surface energy, transparency is lost by Rayleigh scattering. To increase the transparency, research is required to reduce the aggregation of nanomaterials [27]. The plastic detector is composed of a low atomic number material such as C, H, O, so its accuracy is low due to low stopping power and light yield. Because of these properties, plastic scintillators are used in applications such as fast neutron detection, charged particle tracking, and non-destructive testing. Plastic scintillators have advantages over inorganic scintillators such as faster decay time (about 10 ns), non-hygroscopicity, relatively low manufacturing cost, robustness, and processability. Using these advantages, it is possible to develop a plastic scintillator with improved detection efficiency by adding nanomaterials of high atomic number to the plastic matrix [28–36].

In general, Monte Carlo codes are widely used for radiation instrument design, performance evaluation of prototypes, and detector calibration [37–40]. The performance

of the commercial plastic and the CdTe-loaded plastic scintillator was verified through the MCNP simulation. MCNP is a relatively accurate evaluation method for solving a three-dimensional transport equation. In the Monte Carlo method, the spatial structure is simulated exactly as the actual structure and the reaction cross-sectional area is used as a continuous function of energy.

In this study, we elucidated an integrated and portable probe based on a functional plastic scintillator for detection of radioactive cesium. In addition, the results were compared and analyzed with the results of the MCNP simulation.

2. Materials and Methods

2.1. Chemicals

All chemicals and reagents were commercial products. Styrene (99.9%), 2,5-Diphenyloxazole (PPO, >95%), 1,4-bis(5-phenyloxazol-2-yl) benzene (POPOP, >95%), and CdTe used were purchased from Sigma-Aldrich (St. Louis, MO, USA) on a technical purity grade.

2.2. Fabrication of a Functional Plastic Scintillator

A styrene-based plastic scintillator was fabricated by a polymerization method, and its performance was compared and analyzed with a PVT-based commercial scintillator (EJ-200). Plastics were manufactured by the process shown in Figure 2. The materials used in the manufacture of plastics were styrene, PPO (2,5-diphenyloxazole), POPOP (1,4 di[2-(5phenyloxazolyl)]benzene), CdTe, and plastics with a diameter of 50 mm and a thickness of 30 mm. Styrene was used as the primary solvent, PPO was used as the primary fluorophore, and POPOP was used as the secondary fluorophore. Although the types of nanomaterials are various, CdTe was used. The contents (wt%) of organic dye and CdTe were selected due to previous studies [31]. The amounts of materials added to the styrene were PPO (0.4 wt%), POPOP (0.01 wt%), and nanomaterials (0.2 wt%). The plastic scintillator used styrene as a basic matrix material, and a nanomaterial having an emission wavelength range of 500–600 nm was selected. CdTe nanomaterial was mixed with the matrix material, and stirred at 60 °C. After the stirring process for about 2–3 h was completed, the weight suitable for the thickness of the plastic was measured. The sample was placed in a vial for polymerization and fine bubbles generated during stirring were removed. Fine bubbles can cause cracking due to internal stress during the polymerization process, and since it reduces optical properties. Bubble removal process of about 1–2 h is required. The de-bubbled sample is polymerized in a vacuum oven at a temperature of up to 120 °C. At this time, it is important to increase the temperature slowly, and if the temperature is increased rapidly, bubbles in the sample may be regenerated. The polymerization process takes about 70 h. Plastics that have gone through the polymerization process are finished after cutting and polishing the surface to increase the transmittance.

Figure 2. Manufacturing process of a functional plastic scintillator.

2.3. MCNP Simulation

Monte Carlo simulation is a method for solving problems of physical and mathematical systems by generating random numbers and using a probabilistic model. The MCNP code can construct various geometry through the cell card. After modeling the actual geometry through the MCNP computational simulation, the spectrum of the energy accumulated in the scintillator was obtained. And, input data of surface flux in a MCNP 6 simulation was presented in Figure S1.

Figure 3 is the result of calculating the deposited energy for each thickness using MCNP to select the plastic scintillator thickness. The energy of the incident photon is deposited through interaction as it passes through the scintillator. Figure 3a shows the geometry for computational simulation, and the Cs-137 radiation source was placed 20 mm away from the plastic surface. Figure 3b shows the flux by thickness, and Figure 3c shows the energy spectrum by thickness. In this study, a plastic scintillator was fabricated with a thickness of 30 mm showing about 70% energy deposition.

Figure 3. The geometry used in the MCNP computational simulation for the selection of plastic thickness (a), flux by thickness (left), configuration of geometry (right) (b), energy spectrum by thickness (c).

Figure 4 shows the geometry for computational simulation of a plastic detector manufactured with a selected 30 mm thickness. The distance of the radiation source was set to 20 mm, 50 mm, and 100 mm under the same conditions as the experiment, and the gamma energy emitted from the radiation source was set to emit only a single energy of interest. Here, only one detector and one source are simulated, and the surrounding environment is

not considered because it was not expected to have a significant impact on scattering. The size of the radiation source is 2.5 cm in diameter and the location of the source was used as a point in the simulation.

Figure 4. Geometry for computational simulation of 30-mm-thick plastic scintillators.

It was also set up using a Gaussian energy broadening (GEB) card to obtain the ideal Compton spectrum of the plastic scintillator. As the parameters for GEB in Equation (1), values of a , b , and c were applied as 0.00093789, 0.00498, and -0.05999 , respectively. And, all input data of energy spectrum were presented in Figure S2.

$$\text{FWHM} = a + b\sqrt{(E+cE^2)} \quad (1)$$

Here, FWHM means full width at half maximum, E means gamma-ray energy.

The spectrum derived through the MCNP simulation was compared with the actual measurement spectrum, and since the photopeak did not appear due to the characteristics of the plastic scintillator, the detection efficiency was calculated using the gross counts. To make the statistical uncertainty of the calculation result less than 5%, 10^9 photons were generated in each geometry to calculate the measurement efficiency of the plastic detector.

2.4. Manufacturing of Integrated Functional Plastic Detection System

To evaluate the performance of the CdTe-loaded plastic detector, a plastic detection system was constructed as shown in Figure 5a. Additionally, the signal generated from the plastic detector is amplified through a preamplifier and amplifier, and the amplified analog signal is digitized through a multi-channel analyzer and then stored. A high voltage was applied to the plastic detector so that the generated electrons were collected by the electrode. The system was constructed using PMT (ET-9266KB, ET-Enterprises Ltd., Uxbridge, UK), power supply (DT5423, CAEN, Viareggio, Italy), Preamp (Amcrys 544, Amcrys Ltd., Kharkiv, Ukraine), Amp (DT5781, CAEN, Viareggio, Italy), and MCA (DT5781, CAEN, Viareggio, Italy). Additionally, the plastic detector and data processing system were manufactured as an integrated system, so that the integrated system can be used as a portable detection system as shown in Figure 5b. Figure 5c shows a schematic illustration for plastic detection system. The integrated box can contain a data processing system, which is custom-made using an anti-shock sponge. Additionally, it was stored in a dark room for about 12 h after replacing the scintillator to remove the afterglow of the PMT that occurred while replacing the plastic scintillator.

Figure 5. (a) Real picture of the performance experimental setup for gamma energy spectrum using a functional plastic scintillator. (b) Real picture of integrated device box and portable probe with a functional scintillator. (c) Schematic illustration for plastic detection system.

3. Results and Discussion

The transparency of the plastic scintillator decreases due to the coagulation of nano-materials with high surface energy and precipitation during the plastic polymerization process, which may adversely affect the optical properties. Therefore, for the transparency of the plastic scintillator, it is necessary to be careful in the processes of stirring, bubbles removal, slow heating, slow cooling, and polishing. Figure 6a shows the transparency of the CdTe-loaded plastic, and Figure 6b,c show the UV-Vis absorption and PL emission spectra of the plastic scintillator. The absorption peak was confirmed at about 250–400 nm, and 475 nm emission was observed under 316 nm excitation.

As mentioned in the introduction, incident photons tend to deposit all the energy on the photoelectrons generated by interacting with CdTe, a nanomaterial of high atomic number, through the photoelectric effect. This energy goes through an energy cascade process, where the plastic matrix and dye are excited to generate excitons. Energy transfer characteristics are maximized through fluorescent dyes. Typically, through the FRET process, energy is transferred between molecules. As the nanomaterials were loaded, the emission wavelength shifted through the FRET process and the emission intensity increased. This means that compared to conventional fluorescent dyes, quantum efficiency is increased due to nanomaterials, and thus greater fluorescence is generated.

Figure 6. (a) A functional plastic scintillator including CdTe. (b) UV-Vis absorbance. (c) Photoluminescence emission spectrum, excitation at 316 nm.

To compare the performance of a plastic scintillator produced by adding CdTe material with a commercial scintillator, a measurement test was performed by placing a source at a distance of 20 mm from the scintillator surface. Considering the half-life, the radioactivity of the Cs-137 source is 342.28 kBq. Unlike inorganic scintillators, plastic scintillators rarely generate photoelectric effects, and Compton scattering mainly occurs. Compton edge energies of Cs-137 used in this experiment are 477.3 keV. Since the plastic scintillator is dominated by Compton scattering, energy calibration was performed using the Compton edge and measurement tests were performed for 10 min. The results of the measurement test using a point source for each plastic scintillator are shown in Figure 6. Additionally, the result of calculating the output by gross count of the measured spectrum is shown in the Table 2. The relative efficiency of the CdTe-loaded plastic scintillator was calculated using Equation (2) as the gross counting method for the commercial plastic scintillator, and as a result, it was confirmed that it increased by 25% compared to the commercial plastic scintillator. However, the measurement result using the point source analyzed that the Compton edge of commercial plastics has better resolution. This is because of the transmission loss due to Rayleigh scattering, and aggregation of a solid form CdTe nanomaterials.

Table 2. Compared relative efficiency for detection of radioactive cesium.

		Net Count (cps)	Relative Efficiency (%)	Detection Efficiency (%)
Commercial plastic	20 mm	3,644,431 ± 495,634	100.00	2.09
	50 mm	1,332,009 ± 99,208	100.00	0.76
	100 mm	474,203 ± 23,352	100.00	0.27
Plastic without CdTe	20 mm	1,803,557 ± 2657	49.49	1.03
	50 mm	781,528 ± 582	58.67	0.45
	100 mm	303,323 ± 53	63.96	0.17
Plastic with CdTe	20 mm	4,100,748 ± 558,312	112.52	2.35
	50 mm	1,608,902 ± 120,952	120.79	0.92
	100 mm	593,654 ± 331	125.19	0.34

In addition, the detection efficiency of commercial plastics and the CdTe plastic scintillator was measured. The detection efficiency was calculated using Equation (3). In Table 2, the gross count rate increased as the CdTe nanomaterial was added. This means that the high atomic number of CdTe increases the reaction rate with photons, thereby improving the efficiency.

$$\text{Relative efficiency (\%)} = \frac{\text{Total counts (CdTe loaded plastic)}}{\text{Total counts (Commercial plastic)}} \times 100 \quad (2)$$

$$\text{Detection efficiency (\%)} = \frac{\text{Net counts(cps)}}{\text{Radioactivity(Bq)} \times \text{Release Probability(\%)}} \times 100 \quad (3)$$

Figure 7 shows the spectrum measured by radiation source distance for commercial plastics, plastics loaded with CdTe, and plastics not loaded with CdTe. The spectrum in Figure 7 shows the net count minus the background radiation, and is a graph normalized to 477.65 keV, the Compton edge energy of Cs-137. Spectral data were obtained by dividing the energy of 3 MeV by a total of 8192 channels. It was confirmed that as the distance of the radiation source increased, the number of counts decreased.

Figure 7. Normalized energy spectrum by distance. (a) Commercial plastic scintillator. (b) Plastic scintillator with CdTe. (c) Plastic scintillator without CdTe.

Figure 8 represents the measurement data for three plastic scintillators, and it means the average value of the measured data by distance. As shown in Figure 8, it was observed that in the case of the scintillator to which the nanomaterial was added, the Compton peak was shifted to the left compared to the commercial scintillator. Based on this, the light yield

for the CdTe scintillator was calculated using the light yield of EJ-200. Light yield was calculated based on the data in Figure 8 and Equation (4) [41].

$$LY_{Cd} = LY_{EJ} \times \frac{CE_{Cd}}{CE_{EJ}} \times \frac{QE_{EJ}}{QE_{Cd}} \quad (4)$$

Figure 8. Gamma measurement spectrum of three plastic scintillators using Cs-137 point source. Insert figure represents relative counts from channel 1000 to 1800.

Here, LY, CE, and QE refer to the light yield, the peak channel of Compton's edge, and the quantum efficiency of PMT at the emission wavelength, respectively, and EJ and Cd refer to the commercial scintillator and the plastic scintillator loaded with CdTe, respectively. As shown in Table 3, the LY_{EJ} value was used as a reference value of 10,000 photon/MeV, a value suggested by Eljen technology. In addition, QE used the values in the datasheet of PMT (ET-9266KB) [42]. When CdTe was loaded, it was confirmed that the light yield increased compared to commercial plastic scintillator. Based on this result, it is analyzed that the CdTe nanomaterial not only increases the reaction rate with photons, but also improves the energy transfer rate.

Table 3. Compared relative light yield by distance to Cs-137 gamma ray source.

Terms	20 mm	50 mm	100 mm
CE_{Cd}	1295 ch	1298 ch	1291 ch
CE_{EJ}	1430 ch	1444 ch	1434 ch
QE_{Cd}		0.15%	
QE_{EJ}		0.2%	
LY_{EJ}		10,000 photon/MeV	
Relative LY_{Cd}	12,075 photon/MeV	12,103 photon/MeV	12,037 photon/MeV

Figure 9 shows the result of comparing the spectrum of commercial plastic scintillator (EJ-200) and CdTe-loaded plastic scintillator with MCNP simulation. The average relative error in the Compton edge region was analyzed to be within 5%. In the MCNP simulation results of Figure 7b, a signal was detected in a region larger than the Compton edge by CdTe with a high atomic number. The reason that these signals are not seen in the experimental results is likely due to the aggregation due to the low solubility and high surface energy of CdTe. In order to analyze the influence of CdTe nanomaterials, the count ratio was calculated through the Equation (5). As a result, it showed a high coefficient ratio

at the Compton edge energy of Cs-137. In addition, a ratio above '1' means that the CdTe nanomaterial improved the light yield in the polymer corresponding to each channel. In this study, according to the Figure 10, it is shown that there is an improvement of more than 10% by CdTe nanomaterials. The count rate was greatly improved in the 477 keV Compton energy region by CdTe nanomaterials. In addition, the results analyzed below '1' indicate that the effect of nanomaterials may be the effect of light loss and signal overlap due to aggregation of nanomaterials.

$$\text{Count ratio} = \frac{\text{count rate per channel [PS(PPO, POPOP) - CdTe]}}{\text{Count rate per channel [PS(PPO, POPOP)]}} \quad (5)$$

Figure 9. Normalized results from measured and simulated energy spectrum of commercial and CdTe-loaded plastic scintillator to Cs-137 gamma ray source. (a) Point source measurement using commercial plastic scintillator. (b) Point source measurement using a functional plastic scintillator including CdTe.

Figure 10. Count ratio from gamma spectra from a functional plastic scintillator.

CdTe nanoparticles have advantages such as the change of energy gap according to the size of nanomaterials, light emission due to the discontinuity in energy state density, increase in light efficiency, and light emission (even at room temperature) due to the increase in the binding energy of excitons. Until now, there have been a great deal of studies for use in CdTe nanoparticles, like optical materials, as shown in Table 4, and important studies are being conducted to improve the energy transfer rate by doping inorganic particles into CdTe nanoparticles.

Table 4. Progress of CdTe-enabled optical materials.

Nanomaterials	Methods	Results	Year	Ref.
CdTe/BaFBr:Eu ²⁺ nanocomposite phosphors	<ul style="list-style-type: none"> - CdTe QD is weak in X-ray emission, so a CdTe/BaFBr:Eu²⁺ nanocomposite was prepared to evaluate its property. - Analyze the size and structure of nanoparticles by TEM. 	<ul style="list-style-type: none"> - Strength increases as energy is transferred from Eu²⁺ to CdTe QD. - As it can be emitted in the near infrared range (650–1100 nm), which is a tissue optical window for in vivo imaging, the possibility of using it as a semiconductor/phosphor nanocomposite material is evaluated. 	2006	[43]
CdTe quantum dots and polymer nanocomposites	<ul style="list-style-type: none"> - After synthesis by adding CdTe QD having various emission ranges to PMMA-based materials, the applicability to the X-ray imaging field was evaluated. - A nanocomposite film containing 0.1–10 wt% of CdTe QD was prepared and the characteristics were evaluated. - Use of bulk polymerization method to secure transparency 	Excellent X-ray emission results including high resolution, fast decay time, afterglow prevention, high stopping power, and excellent spectral matching to the CCD detector	2011	[44]
LaF ₃ :Cd/CdTe nanocomposites	<ul style="list-style-type: none"> - LaF₃:Ce/CdTe nanocomposite was prepared to observe the X-ray emission characteristics of CdTe QD - Analyze the size and structure of nanoparticles through TEM 	<ul style="list-style-type: none"> - The X-ray emission of CdTe QD is very weak, but the emission of LaF₃:Ce/CdTe increases (six times) - CdTe QD shows the characteristics of intense photoluminescence and up-conversion light emission, and short decay time characteristics 	2012	[45]
CdTe Photovoltaic Devices	<ul style="list-style-type: none"> - In order to improve the performance of the CdTe-based solar cell, the developed CdCl₂ heat treatment was applied to the CdTe of the upper layer structure in which most of the reactions occur. - Improved efficiency by controlling the junction of CdTe-based solar cells 	<ul style="list-style-type: none"> - CdTe is widely used due to the simplicity of the structure and the efficiency compared to the doped amount, and the efficiency of the CdTe-based solar cell is improved through the CdCl₂ heat treatment method. - By improving the characteristics of the interface layer (IFL), it shows an efficiency of 10.97%. 	2012	[46]
CdTe quantum dots synthesized using 3-mercaptopropionic acid reduction of tellurium dioxide	<ul style="list-style-type: none"> - A facile one-step synthesis of CdTe quantum dots (QDs) in aqueous solution by atmospheric microwave reactor has been developed using 3-mercaptopropionic acid reduction of TeO₂ directly. - The obtained CdTe QDs were characterized by ultraviolet–visible spectroscopy, fluorescent spectroscopy, X-ray powder diffraction, multifunctional imaging electron spectrometer (XPS), and high-resolution transmission electron microscopy 	<ul style="list-style-type: none"> - Green to red-emitting CdTe QDs with a maximum photoluminescence quantum yield of 56.68% were obtained. - The as-synthesized CdTe QDs were highly luminescent, which ensures their promising future applications as biological labels 	2013	[47]
Plastic scintillator containing Gd ₂ O ₃ or CdTe	<ul style="list-style-type: none"> - A plastic detector is manufactured by adding a fluorescent material and a nano material (Gd₂O₃ or CdTe) to an epoxy-based material. - Evaluating the efficiency using a beta source (Sr-90) 	<ul style="list-style-type: none"> - As a result of characterization evaluation after adding the concentration of QD by 0.05–1 wt%, 0.1 wt% was analyzed as the most optimized concentration. 	2019	[36]

Table 4. Cont.

Nanomaterials	Methods	Results	Year	Ref.
Silver ion-doped CdTe quantum dots	<ul style="list-style-type: none"> - This is a study to use CdTe QD as a fluorescent probe for Hg^{2+} detection - To expand the detection concentration range of Hg^{2+}, Ag ions were doped with CdTe QD - The characteristics of the produced QD were analyzed. 	<ul style="list-style-type: none"> - As a result of investigating the release mechanism of Ag-doped CdTe QD, it shows multiple release in QD samples with high Ag^+ doping concentration - The highest PL quantum yield of the QD sample was analyzed as 59.4% 	2020	[48]
Thioglycolic acid-capped CdTe quantum dots	<ul style="list-style-type: none"> - Develop CdTe QD synthesis method to improve quantum yield - Evaluating the characteristics of specific substances (SAL) by concentration through fluorescence quenching mechanism - Using the ratio of $[Cd^{2+}]:[HTe]:[TGA(Thioglycolic\ acid)] = 1:0.5:2.4$, CdTe QD with high photoluminescence was synthesized at 140 °C. 	<ul style="list-style-type: none"> - Synthesizing CdTe with an emission wavelength of 540–560 nm and evaluating the possibility of using it for SAL detection - Evaluating the concentration of additives (SAL) using the degree of extinction of QD 	2021	[49]
Non-polar PMMA solvent of CdTe quantum dots by silica coating	<ul style="list-style-type: none"> - Using CdTe coated with SiO_2 ($CdTe@SiO_2$) and PMMA, a nanocomposite material was produced that efficiently exhibits Stokes shift - The characteristics of CdTe coated with silica and without silica were compared and analyzed. 	<ul style="list-style-type: none"> - In the PMMA/CdTe thin film without silica coating, non-uniform CdTe particles act as defects in the matrix. - In the PMMA/CdTe thin film coated with silica, clusters of uniform size were observed. - The emission spectrum of SiO_2 overlaps with the excitation wavelength range of CdTe QD to increase the response of the optical system 	2021	[50]
CdTe quantum dots using a binary solvent (water and glycerin)	<ul style="list-style-type: none"> - Comparison of optical and structural characteristics between CdTe QDs - Analyzing the optical properties of CdTe nanocrystals made with various synthesis parameters 	<ul style="list-style-type: none"> - The optical properties of CdTe QD showed the highest emission quantum yield when synthesized with a binary solvent. - CdTe QD prepared with a Cd:Te molar ratio of 20:1 showed a narrow photoluminescence band and improved quantum yield 	2021	[51]
CdTe quantum dots and graphene quantum dots	<ul style="list-style-type: none"> - A study on the spectral characteristics of a wide range of CdTe quantum dots and wide-gap graphene QD was conducted. - A technology to replace the organic shell of CdTe QD of various sizes was proposed. - Light stability when irradiated with radiation on CdTe QD and wide-gap graphene quantum dots was compared and analyzed. 	<ul style="list-style-type: none"> - Colloidal graphene quantum dots and CdTe investigated in this work retain their optical and structural properties when exposed to radiation in the visible range - In the case of CdTe QD, the maximum intensity of the irradiated sample did not change within the measurement error, but in the case of graphene QD, the intensity decreased when irradiated with ultraviolet rays. 	2021	[52]
CdTe/PPO/POPOP/Polystyrene	<ul style="list-style-type: none"> - Monolith-typed functional plastic scintillator having a diameter of 50 mm and a thickness of 30 mm was manufactured by adding 2,5-diphenyloxazole (PPO, 0.4 wt%), 1,4 di[2-(5phenyloxazolyl)]benzene (POPOP, 0.01 wt%), and CdTe (0.2 wt%) materials in a styrene-based matrix. 	<ul style="list-style-type: none"> - Integrated and portable probe based on a functional plastic scintillator for detection of Cs-137. - Remarkable performance of the functional plastic scintillator was confirmed through comparative analysis with Monte Carlo simulation. 	2021	This work

4. Conclusions

In this study, we elucidated an integrated and portable probe based on functional plastic scintillator for detection of radioactive cesium. The performance of the CdTe-loaded plastic scintillator was compared with a commercial plastic scintillator. The performance of the CdTe-loaded plastic scintillator was analyzed using Cs-137 point source. After setting the distance between the radiation source and the detector to 20 mm, the energy spectrum was analyzed, and the reliability of the result was secured by comparing with the MCNP simulation result. When the functional plastic scintillator equipped with CdTe was compared with the commercial plastic scintillator, the relative efficiency increased by up to 25%, and the detection efficiency was also increased. In addition, as a result of calculating the relative light yield based on the light yield of the commercial plastic scintillator, it was confirmed that the light yield increased when CdTe was loaded. It is expected that a high-efficiency and high-sensitivity plastic detection system can be developed by optimizing the amount of nanomaterials in the future and can be applied the measurement data processing methodology. Finally, the highly reliable and direct detection of radioactive cesium based on an integrated portable probe including a functional plastic scintillator will pave the way for potential interest due to in situ detection and monitoring in environmental sites for nuclear facilities and radiation measurements.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/app1115210/s1>. Figure S1: Input data of surface flux in a MCNP 6 simulation; Figure S2: Input data of energy spectrum in a MCNP 6 simulation.

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