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Wireless Backpack System for Detection of Radioactive Cesium on Contaminated Soil Using Portable Plastic Scintillator with Efficient Readout Device

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Abstract: The miniaturization and usability of radiation detectors make it increasingly possible to use mobile instruments to detect and monitor gamma radiations. Here, a Bluetooth-based mobile detection system for integrated interaction in a backpack was designed and implemented to smart equipment for the detection of radioactive cesium on contaminated soil. The radiation measurement system was demonstrated in the form of a backpack using a quantum dot (QD)-loaded plastic scintillator manufactured and prepared directly in this study, and it can be measured by a person in the wireless framework of integrated interaction. The QD-loaded plastic scintillator was measured after setting the distance from the contaminated soil to 20, 50, and 100 mm. As a result, the detection efficiency of the commercial plastic scintillator (EJ-200) was calculated to be 11.81% and that of the QD-loaded plastic scintillator was 15.22%, which proved the higher detection efficiency performance than the commercial plastic scintillator. The measurement result was transmitted to a personal computer using Bluetooth as a portable system. In the future, this wireless system design could be expanded as a wireless communication system equipped with a global positioning system to detect and measure radioactively contaminated environments.

Keywords: sensors; wireless measurement; plastic scintillator; radioactive cesium; contaminated soil

1. Introduction
Radioactive materials released into the atmosphere during a nuclear accident are exposed to humans through two routes. There is external exposure through the atmosphere and the ground, and internal exposure caused by human ingestion of food and drinking water contaminated with radioactive materials [1,2]. However, in addition to nuclear accidents, there is a possibility that the surrounding environment may be contaminated due to radioactive materials emitted due to micro-defects in the operation of nuclear facilities. When dismantling a nuclear facility, radiological characterization and radiation monitoring must be performed. After dismantling, it must be proven that the residual contamination level of the decommissioning site is below the release criteria, which means site release criteria. In addition, the maximum radiation dose of 0.25 mSv/y is applied as the maximum radiation dose for residual contamination as a representative of the NRC site release standard.
For this purpose, it is necessary to have a measurement and evaluation technique that can be applied to the field and has high reliability. In general, soil samples from the contaminated area are collected and then the contamination level is evaluated through a pretreatment process. Although the sampling method has high accuracy, it is costly and time-consuming due to sampling and preprocessing [3–5]. In addition, in situ gamma-ray spectroscopy is a useful method to directly identify radioactive materials in a wide area of applications, such as nuclear accidents or nuclear material detection. With direct measurement of surface contamination using equipment such as a survey meter, accurate nuclide analysis is difficult, and it is impossible to use in narrow equipment, such as pipes. In addition, it is inefficient in measuring a large area, such as a nuclear decommissioning site [6–8]. Importantly, accurate radiological contamination characteristics should be evaluated to dispose of or recycle various types of wastes generated during the decommissioning of nuclear facilities.

In most nuclear facilities and nuclear decommissioning fields, semiconductor radiation detectors and inorganic scintillators are used to measure site residual radioactivity or to perform radiological characterization of contaminated wastes. A material that emits light when irradiated with radiation is called a scintillator, and the types of scintillator can be divided into solid, liquid, and gas scintillators. Solid scintillators are divided into organic scintillators and inorganic scintillators. A detector that measures radiation by counting photons generated from the scintillator is called a scintillation detector [9–15]. In addition, plastic scintillators that can be easily changed in size and shape are economically manufactured. In general, plastic scintillators are composed of low atomic number materials, are mainly used for alpha and beta measurement, and have disadvantages in that it is difficult to analyze nuclides due to poor resolution. Since the currently operated radiation monitoring system cannot distinguish nuclides, a time delay occurs due to false alarms and unnecessary secondary search. This also incurs additional regular costs [16–19].

Gamma nuclide-related studies have been mainly performed using inorganic scintillators, and studies utilizing a plastic scintillator were mainly applied to determine the presence of radioactive materials, or neutron imaging studies [20–25]. Many studies on the development of a high-performance plastic scintillator that could be used for gamma-ray measurement while having the advantages of a plastic scintillator by adding a high atomic number material to the plastic matrix have been conducted recently [26–31]. There are several ways to combine the advantages of organic and inorganic scintillators for the purpose of detecting ionizing radiation. First, an inorganic single crystal and an organic compound are alternately layered. This structure enables efficient energy absorption in the high-Z layer due to the high stopping power of the inorganic compound. Organic compounds mainly serve as sources of emission generated by interaction with the recoil electrons formed in the high-Z layer. Second, high atomic number quantum dots are dissolved in common organic scintillation materials. Third, the development of nanocomposite materials by synthesizing inorganic nanoparticles and polymers [30]. Until now, many studies have been conducted by dissolving quantum dots in organic scintillation materials, and research on the quantum dot synthesis method has been accelerated since the Bawendi group at MIT reported a highly efficient cadmium-based quantum dot synthesis method in the 1990s. Currently, a variety of quantum dots have been reported, including the cadmium series II-VI, III-V, IV-VI, and I-III-V [32,33].

The in-site measurement method includes a method of measuring by installing a detector on a moving vehicle or installing a radiation detection system at the measurement site. In addition, there is a method for people to directly measure with equipment in areas where the measurement site is narrow or where vehicle access is not possible [34,35]. Recently, many mobile detection systems, such as vehicles, backpack, and drone types, have been developed. In 2019, Ji’s research team conducted a site measurement study [36] using a 2-inch LaBr$_3$(Ce) detector for backpack type. Moreover, the radioactivity mapping function was added by using GPS, communication modules, as well as the LaBr$_3$(Ce) detector, and the location of hot-spots and the depth of contamination were evaluated.
In the case of a large area, such as a nuclear facility decommissioning site, in situ large-size measurement systems or mobile rapid measurement systems are required. In situ measurement systems are economical and efficient because they can quickly measure radioactive contamination in the field [37–43]. Currently, radiation safety management-related organizations manage the use of radioactive materials or the results of radiation monitoring through a global positioning system (GPS). In addition, there is a trend to establish a remote monitoring system and a wireless information network to prevent loss of radiation sources. The establishment of a radioactive remote monitoring system not only prevents the loss of radiation sources, but also prevents the occurrence of emergency accidents, such as radioactive material leakage, and enables a quick response in the event of an accident [44–46]. However, these systems are not installed at regular intervals around nuclear facilities. In addition, it is difficult to predict the behavior of radionuclides in the event of a radioactive material leakage accident [47–49]. Until now, there has been no means to evaluate the behavior of radioactive materials, other than the predicted scenarios through simulation. Eventually, the wireless radiation monitoring system is needed to prevent emergency accidents for accurate prediction and evaluation.

In this study, a Bluetooth-based wireless mobile system in a backpack consisting of all components for the detection of radioactive cesium on contaminated soil using a portable plastic scintillator with an efficient readout device was demonstrated. A mobile detection system was developed using a quantum dot (QD)-loaded plastic scintillator instead of an inorganic scintillator. Characterization of the QD-loaded plastic scintillator was performed, and a sample simulating soil contaminated with $^{137}$Cs was prepared to evaluate the performance of the developed detection system. The concept and proof of the concept of this study are shown in Figure 1. The concept of Figure 1 presents the items performed in this study, and Figure 1C shows an item to be performed in the future based on the verification data of the performance of the QD-loaded plastic scintillator. As shown in Figure 1A,B, it was elucidated that the QD-loaded plastic scintillator has improved performance compared to the commercial plastic scintillator to measure radioactive cesium on contaminated soil. If an operator works for a long time in an environment with severe radiation exposure, the worker may be damaged, so it is necessary to constantly monitor the radioactivity in a safe zone. Such precaution is very important and becomes an issue in basic management of safety in radioactively contaminated areas. As shown in Figure 1C, it is confirmed to secure the safety of radiation safety managers, workers, and accident handling managers that can measure gamma radiation on measurement technology and wireless communication technology accurately and quickly.
Figure 1. The overall schematic illustrations of a wireless mobile system for the detection of radioactive cesium on contaminated soil. (A) Manufacturing of plastic scintillator and optical properties. (B) Radiological measurement using a contaminated soil plate and performance evaluation of QD-based plastic scintillator. (C) Manufacturing and application of mobile and wireless communication systems.

2. Materials and Methods

2.1. Fabrication of Plastic Scintillator

Styrene-based plastic scintillators, which were fabricated through the thermal polymerization method with monomer styrene, 2,5-Diphenyloxazole (PPO), 2,2-p-phenylene-bis(5-phenyloxazole) (POPOP), and CdS/ZnS. Styrene, PPO, POPOP, and CdS/ZnS (oleic acid functionalized, λem = 450 nm, 5 mg/mL in toluene) were purchased.
functionalized, λ_{em} = 450 nm, 5 mg/mL in toluene) were purchased from Sigma-Aldrich (St. Louis, MO, USA). Styrene was used as the primary solvent, PPO was used as the primary fluorophore, and POPOP was used as the secondary fluorophore. The optimum value calculated in the previous study [50] was used. The amounts of materials added to styrene were PPO (0.4 wt%), POPOP (0.01 wt%), and nanocrystals (0.2 wt%). The thermal polymerized plastic scintillators of 50 mm diameter were manufactured in 30 mm and 50 mm thickness for performance comparison by volume. In principle, the primary solvent material converts the kinetic energy of radiation particles into excitation energy, and the primary fluorophore converts the excited energy into light. Secondary fluorophore shifts the wavelength of light. Lastly, nanocrystals improved the detection efficiency and the luminous efficiency by increasing the electron trap rate and collision probability. The plastic scintillator used styrene as a basic matrix material, and a nanocrystal having an emission wavelength range of 400 to 500 nm was selected. Currently, Cd-series nanocrystals are widely used because their performance has been proven through many studies [51–56].

Nanocrystal was mixed with the matrix material and stirred at 60 °C. 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 because they reduce optical properties. A bubble removal process of about 1~2 h is required. The de-bubbled sample was 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 S1 is a diagram showing a plastic manufacturing process using styrene and fluorescent materials. Since the plastic cutting and polishing process requires a precision process for transparency and balance of the sample, it was requested to a specialized company. In order to evaluate the optical properties of the QD-loaded plastic scintillator, absorption/transmission and fluorescence properties were observed. First, absorption/transmission spectra were obtained using an optical spectrometer of Ocean Optics. As shown in Figure S2, this system consists of a spectrometer, a light source (DH-2000), two optical fibers, and a sample holder. The DH-2000 light source combines continuous spectra of deuterium and tungsten halogen light sources in a single optical path. The combined spectral light source produces a stable output from 215 to 2000 nm. Moreover, a deep-UV light source with a wavelength range of 190 to 1700 nm can be used. The two optical fibers have a core diameter of 400 µm and a wavelength range of 300~1100 nm is possible.

### 2.2. Manufacture of Radioactive Cesium on Contaminated Soil

In this study, not only was the performance of a functional plastic scintillator evaluated using point source, but also the performance of the QD-loaded plastic detector was verified using a soil plate sample that simulates soil contaminated with ^{137}Cs. Since radioactive materials interact with elements in the soil, the total energy decreases and the probability of Compton scattering increases as the depth distribution of the source increases. Thus, the radioactivity of the soil surface is related to the amount of radioactive material and the extent and depth of the contamination. However, in this study, the radioactivity according to the depth was not considered. For comparison of measurement efficiency, soil plate samples were prepared to realize a contaminated soil environment. Contaminated soil plate samples with different specific radioactivity were prepared by mixing ^{137}Cs, which is used as an indicator for the analysis of the contamination level of the nuclear power plant site, in commercial soil (Daemyung Chemical, SiO_2 97%). Contaminated soil was manufactured with a plate-shaped source of 500 × 500 × 40 mm using immobilizing agent. The immobilizing agent was used by mixing polydiallyl dimethylammonium chloride (PDADMAC, PDDA):polyacrylic acid (PAA):KCl:NaOH in a ratio of 40:6:1.5 (wt%). In addition, the same amount (wt%) of H_2O was added to the mixture, and the mixture was
uniformly mixed with contaminated soil in a 1:3 (wt%) ratio. In addition, it was dried at room temperature for 1 week. Soil plate samples (500 × 500 × 10 mm) of 10 Bq/g were prepared by mixing soil, an immobilizing agent, water, and 137Cs sources on an acrylic plate. In total, 10 Bq/g soil plate samples were used by overlapping 4 plates of 10 Bq/g. The 10 Bq/g soil plate sample was calculated as 100,000 Bq when considering density and volume. Moreover, measurement experiments were performed at a distance of 20, 50, and 100 mm from the soil plate sample (Figure 2), similar to the measurement experiment using point sources. To compare the performance of a plastic scintillator produced by adding CdS/ZnS as a nanocrystal material with a commercial scintillator, a measurement test was performed by placing a radiation source at a distance of 20, 50, and 100 mm from the scintillator surface with a system constructed. According to the detection characteristics of plastics, the Compton edge was analyzed by showing the continuous spectrum characteristics.

![Figure 2. Manufacturing process of contaminated soil with 137Cs.](image)

### 2.3. Radiation Measurement

The analysis of radiation measurement was performed based on the Compton edge energy of 137Cs. The Compton energy of 137Cs is calculated as 477.3 keV through Equation (1).

\[
\hat{h}v' = \frac{hv}{1 + \frac{hv}{m_0c^2(1 - \cos\theta)}}
\]  

(1)

Here, \( h \) is Planck’s constant, \( m_0 \) is the rest mass of electrons, \( c \) is the speed of light, \( \theta \) is the scattering angle of the incident photon, \( \nu \) is the frequency of the incident photon calculated as \( c/\lambda \), \( \nu' \) is the frequency of the scattering photon calculated as \( c/\lambda' \), and \( \lambda \) and \( \lambda' \) mean the wavelengths of incident photons and scattered photons, respectively.

The wavelength of the incident photon depends on the scattering angle of the photon and, when the scattering angle is 180°, the electron’s kinetic energy is maximized while backscattering [19]. This is called the Compton edge. Before performing this experiment, the MCA was set to analyze up to 3 MeV of gamma-ray energy using an 8192 channel, and channel calibration was performed using a point source. A point source of 137Cs was used. In addition, the point source was located at 20 mm from the plastic scintillator to perform channel calibration. A commercial plastic (EJ-200, Eilen Technology, Sweetwater, TX, USA) and CdS/ZnS-loaded plastic with a diameter of 2 inches were connected with a 2-inch PMT (ET-9266KB, ET-Enterprises Ltd., Uxbridge, UK), respectively. In addition, signals extracted from PMT were processed by MCA (MCA123E) with built-in Amp and high voltage. In a backpack system, a self-manufactured MCA consisted of a printed circuit board (PCB).
3. Results
3.1. Characterization of Plastic Scintillator Fabricated

Absorption/transmission characteristics were performed on a QD-loaded plastic scintillator and commercial plastic scintillator. The optical properties were observed for both the 30 mm and 50 mm sizes of the plastic scintillator thickness. The absorption/transmission characteristic evaluation results are shown in Figure 3. The commercial plastic scintillator and QD-loaded plastic scintillator each showed the same absorption and transmission properties, regardless of the thickness. The absorption and transmission intensity were measured differently for each surface of the scintillator. In this study, 10 points were randomly selected and measured in the circumferential direction, and the average value was calculated. The results of photoluminescence characteristics of the fabricated plastic scintillator were obtained using a spectrofluorometer (HORIBA, Fluorolog3). The photoluminescence spectroscopy characteristic of the existing equipment can be measured up to 10 mm, so only the sample size adjustment space of the holder is made separately, so that 30 mm and 50 mm samples can also be measured. Figure S3 shows the spectrophotometer used in this study and it shows the real photo after mounting 30 mm and 50 mm samples. The photoluminescence lifetime of fluorescent material is affected by both the radiative and nonradiative transition processes of excited electrons. Radiative transition is determined by the molecular structure of the phosphor itself, and the nonradiative transition has the characteristic of being sensitively changed by phosphor–phosphor interaction, phosphor–solvent interaction, and energy transfer.

![Figure 3.](image)

Figure 3. Absorption and transmittance measurement results of commercial plastics and CdS/ZnS-loaded plastic scintillators: (a) absorbance; (b) transmittance.

Figure 4 shows the emission spectrum of a plastic scintillator with a 30 mm thickness. The emission peak of 320–350 nm is emission by the primary dye, and the emission peak of 380–420 nm is emission by the secondary dye. In addition, the theoretical emission wavelength of CdS/ZnS QDs is 450–460 nm. Although the intensity was measured to be low due to surface contamination, it was confirmed that the emission of the CdS/ZnS plastic scintillator was more clearly visible at the wavelength of 450 nm. The emission wavelength of the CdS/ZnS-loaded plastic scintillator was similar to that of the commercial plastic scintillator.
3.2. Portable Plastic Detector and Bluetooth-Based Wireless System

Figure 5 is a configuration of a mobile measurement system using a plastic scintillator for this study. The source used in this study was a $^{137}$Cs-contaminated soil and the radioactivity of the source was 10 Bq/g, considering the half-life. Figure 5a shows the view of the plastic detection part. It is manufactured so that plastic scintillators of various thicknesses can be mounted, and PMT (ET-9266KB) and MCA (MCA123E, Amplifier, High-voltage supply) are connected in one module. The power of the manufactured wireless system was supplied using a rechargeable power supply. Since the self-manufactured MCA consists of a high-voltage supply and a printed circuit board (PCB), a separate high-voltage supply device is not required. The detector is connected with a sensor device that generates information through interaction between radiation and matter, and a device that converts radiation information into electrical signals (Preamplifier, Amplifier, MCA, etc.). PMT amplifies the photoelectrons generated by the scintillator and is amplified about $10^6$ times. The preamplifier shapes the current received from the PMT in the form of a pulse and transmits this signal to the main amplifier. The main amplifier (Amplifier) shapes and amplifies the pulse. In addition, MCA classifies and collects pulse signals by pulse height, counts the frequency of pulses per channel, and displays them in a distribution diagram. The plastic scintillator is made of an aluminum casing to reduce the effect of light. However, it was made as thin as possible to minimize the effect of shielding or scattering caused by the aluminum casing. Therefore, the aluminum case was manufactured to be 1.5 mm. Figure 5c shows the case size for a 50-mm-thickness plastic scintillator, and the case size for a plastic scintillator with various thicknesses is presented in Figure S5. All components are manufactured as a set in the form of a backpack in Figure 6, and the measurement data are transmitted to the PC via Bluetooth.

The backpack system weighs about 6 kg, including all devices. Moreover, Bluetooth baud rate (bits per second, bps) refers to the data rate transmitted through the serial line. Based on this value, the time required to transmit 1 bit can be known. The baud rate of Bluetooth used in this system is 115,200 bps. The higher the bps value, the faster the transmission/reception speed, but it cannot exceed 115,200 bps. In general, 10 bits are required to transmit 1 byte, so 115,200 bps is 11.25 Kbyte/s. Detailed information of the backpack system is shown in Table 1.

The fabricated system is in the form of a backpack, but since this study is a preliminary performance evaluation stage of a CdS/ZnS-loaded plastic scintillator, the performance test was performed by placing the $^{137}$Cs-contaminated soil and the mobile detection system close to each other. The distance between the $^{137}$Cs-contaminated soil and the detection system was set to 20, 50, and 100 mm, and data were collected for 600 s. The experimental results were analyzed using a data file (Excel file) that is automatically saved through Bluetooth communication.
Figure 5. Schematic illustration of the plastic detector system. (a) Drawing of the plastic detector. (b) Detailed drawing of the detection part and signal-processing part. (c) Plastic detector size in detailed drawing.
Figure 6. Plastic scintillator-based wireless radiation measurement system. (a) Configuration of backpack-typed wireless system. (b) Components of plastic detection system and connection diagram.

Table 1. Detailed specifications of the backpack system.

| Item                  | Description                                      |
|-----------------------|--------------------------------------------------|
| General               | Size ~340 × 250 × 450 (H) mm                     |
|                       | Weight 6 kg (including backpack cover)           |
| Detection             | Detector Plastic scintillator                    |
|                       | Energy range ~3000 keV                           |
|                       | Power consumption 10 W                          |
| MCA                   | 100,000 cps throughput                           |
|                       | Pulse-integral gate: 100–200 ns                  |
| Power supply          | Commercially available Li-Po battery ~3.85 V, 20,000 mA |

3.3. Measurement of Radioactive Cesium on Contaminated Soil

As shown in Figure 7, the detection characteristics of the commercial plastic scintillator and CdS/ZnS-loaded plastic scintillator were measured using soil contaminated with $^{137}$Cs, and it was observed that the total count of the 50 mm plastic scintillator was higher than that of the 30 mm plastic scintillator. However, the channel of the $^{137}$Cs Compton edge was not shifted, regardless of the thickness of the plastic scintillator. This means that ultraviolet radiation emitted by polystyrene was absorbed by the fluorescent material and was converted into visible light.
The spectra of commercial and CdS/ZnS-loaded plastic scintillators showed similar trends, and the full energy peak expected from the CdS/ZnS-loaded plastic scintillator results was not observed. This is because too little quantum dot content was added, and the quantum dot did not show an effect. However, the total counts were observed to be higher in the quantum-dot-loaded plastic scintillator results than in commercial plastic scintillator results. This proves that quantum dots affect the rate of reaction with incident photons.

In order to verify the results of this study, MCNP simulation was performed under the same conditions as the experimental conditions. The MCNP code is a radiation transmission code developed by Los Alamos National Laboratory. The MCNP simulates individual particle trajectories, and the stochastic events that make up the interaction process of nuclear particles with material are simulated [45].

Energy calibration is usually carried out by the linear relationship between the pulse height and the corresponding energy. The position of the Compton maximum of the measured spectrum (Lmax) can be used as the Compton edge due to the smallest variance to the real Compton edge. For energy above 40 keV, the function for linear fit is given by the following Equation (2):

$$L = c(E_e - E_0)$$

Here, L is the pulse height, $E_e$ is Compton electron energy, $E_0$ is the intercept energy, and c is the slope which is characteristic of the experimental system.

The intercept energy ($E_0$) is 63.11 keV, which represents the nonlinearity because of quenching effects in the plastic scintillator fabricated for small electron energy. Based on the energy calibration obtained from the linear fit, Monte Carlo simulation using MCNP code was conducted under the same condition as the experiment condition. F8 tally for energy spectrum and GEB card for Gaussian energy broadening were used in MCNP code (see Figure S4). The simulated energy spectra were calibrated to the pulse-height spectra, and matched to the measured pulse-height spectra in trial and error for manipulating the parameters of GEB card. The parameters acquired by matching the spectra are the components of Equation (3). The FWHM corresponding to the Compton electron maximum energies ($E_c$) were calculated by using the above equation, and the
energy resolution $\Delta L/L$ was derived by dividing the FWHM ($\Delta L$) with the Compton electron maximum energies ($L$).

$$\text{FWHM} = a + b\sqrt{E_e} + cE_e^2 \quad (3)$$

The results are shown in Figure 8. Due to the influence of the actual surrounding environment, an error occurred between the actual measurement result and the simulation result in 200 channels or less. However, it was analyzed that the measurement result and the MCNP simulation result showed an error of less than 5% for more than 200 channels.

![Comparison of measurement results and MCNP simulation results using 30-mm-thick plastic scintillator.](image)

**Figure 8.** Comparison of measurement results and MCNP simulation results using 30-mm-thick plastic scintillator. (a–c) Comparison of results by distance with a source using a commercial scintillator. (d–f) Comparison of results by distance with a source using a CdS/ZnS-loaded scintillator.

In addition, as a result of performing the test by setting the distance to the soil source as 20 mm, 50 mm, and 100 mm, it was observed that the total count decreased in inverse proportion to the distance in Figure 9.

![Measurement results due to the distance from the contaminated soil sample using a CdS/ZnS-loaded plastic scintillator.](image)

**Figure 9.** Measurement results due to the distance from the contaminated soil sample using a CdS/ZnS-loaded plastic scintillator: (a) 30 mm thickness in a plastic scintillator; (b) 50 mm thickness in a plastic scintillator.
Figure 10 shows the wireless radiation detection system and detection efficiency calculated based on measurement results. Equations (4)–(7) are the statements for calculating relative efficiency and detection efficiency.

Detection efficiency (%) = \( \varepsilon_I \times \varepsilon_G \) (4)

\[ \varepsilon_I = \frac{\text{Net counts (cps)}}{\text{Radioactivity (Bq)} \times \text{Release probability} \times 100} \] (5)

\[ \varepsilon_G = \frac{\Omega}{4\pi} \] (6)

Solid angle \( \Omega \) = \( 2\pi \left(1 - \frac{d}{\sqrt{d^2 + r^2}}\right) \) (7)

Figure 10. (a) Wireless radiation detection system of the CdS/ZnS plastic scintillator and commercial plastic scintillator by soil source position (b) and detection efficiency.

Here, \( \varepsilon_I \) is intrinsic efficiency and \( \varepsilon_G \) is geometrical efficiency. Radioactivity (Bq) is the intensity of the soil source and Net counts (cps) is the total counts for each scintillator. Net count means the value with the background count removed. Table 2 shows the cps values. The release probability is the probability of emitting a 0.662 MeV gamma-ray photon while decaying to \(^{135}\)Ba. Moreover, \( d \) is the distance between the scintillator and the source and \( r \) is the radius of the scintillator.

Table 2. The total count (cps) by plastic type and distance from the source.

| Total Counts (cps) | Commercial 30 mm-th | Commercial 50 mm-th | QD-Loaded Plastic 30 mm-th | QD-Loaded Plastic 50 mm-th |
|--------------------|---------------------|---------------------|---------------------------|---------------------------|
| Distance 20 mm     | 104.4               | 125.3               | 137.6                     | 165.2                     |
| Distance 50 mm     | 92.1                | 110.5               | 113.5                     | 136.2                     |
| Distance 100 mm    | 74.3                | 89.2                | 90.9                      | 109.1                     |

The measurement experiment was performed after locating the contaminated soil, as shown in Figure 10a, and the detection efficiency and relative efficiency were calculated based on the data transmitted through Bluetooth communication. Figure 10b is the calculated detection efficiency. As a result of analyzing the detection efficiency in Figure 9b, the efficiency decreased as the distance between the source and the scintillator increased as expected. The detection efficiency of the CdS/ZnS-loaded plastic scintillator was analyzed to be higher than that of a commercial plastic scintillator.

The average detection efficiency of the CdS/ZnS-loaded plastic scintillator was about 15.22% and the average detection efficiency of commercial plastics was about 11.81%. This proves that quantum dots with a high atomic number increase the rate of reaction with incident photons.
Among the factors showing the performance of the scintillator, the light yield was calculated through Equation (8) [29,57]. The relative light yield of CdS/ZnS-loaded plastic compared to a commercial plastic scintillator showed similar results to 10,000 photon/MeV. To calculate \( \text{LY}_{\text{Cd}} \) in Equation (8), \( CE_{\text{Cd}} \) value is 1304 channel, \( CE_{\text{EJ}} \) value is 1279 channel, \( QE_{\text{Cd}} \) is 21\%, \( QE_{\text{EJ}} \) is 23\%, and \( \text{LY}_{\text{EJ}} \) value is 10,000 photon/MeV. Therefore, the light yield of the CdS/ZnS-loaded plastic scintillator was calculated as 11,166 photon/MeV. The light yield of the CdS/ZnS-loaded plastic scintillator is expected to show superior light yield performance than a commercial plastic scintillator if dispersion, transparency, and quantum yield of the CdS/ZnS-loaded plastic scintillator are improved.

\[
\text{LY}_{\text{Cd}} = \text{LY}_{\text{EJ}} \times \frac{CE_{\text{Cd}}}{CE_{\text{EJ}}} \times \frac{QE_{\text{EJ}}}{QE_{\text{Cd}}}
\]  

(8)

In addition, as a result of calculating minimum detectable activity (MDA) through Equation (9), the commercial plastic scintillator was analyzed as 0.0639 Bq/m\(^3\) and QD-loaded plastic scintillator as 0.0609 Bq/m\(^3\).

\[
\text{MDA (Bq/g)} = \frac{2.71 + 4.65 \sqrt{B}}{(T \ast V \ast \varepsilon \ast K)}
\]  

(9)

Here, \( B \) is the background count during the measurement time (T), \( V \) is the sample volume or mass, \( \varepsilon \) is the detection efficiency, and \( K \) is the recovery factor, which accounts for the decrease in radioactivity due to radioactive decay. The recovery factor was not considered in this study because the detection system was used to measure in situ radiation directly [12].

4. Conclusions

The miniaturization and usability of radiation detectors make it increasingly possible to use mobile instruments to detect and monitor gamma radiations. In this study, we demonstrated a Bluetooth-based wireless mobile system. In a backpack, there contained all components, such as a plastic scintillator, including CdS/ZnS quantum dots, a PMT, an MCA, a controller, a Bluetooth, and HIV supply, for detection of radioactive cesium on contaminated soil. Eventually, a portable plastic scintillator with an efficient readout device was demonstrated for wireless radiation detection. A mobile detection system was developed using a quantum-dot-loaded plastic scintillator instead of an inorganic scintillator. Characterization of the quantum-dot-loaded plastic scintillator was performed and a sample simulating soil contaminated with radioactive cesium was prepared to evaluate the performance of the developed detection system. Based on the results of this study, the possibility of a CdS/ZnS-loaded plastic scintillator as an alternative to inorganic scintillators has been demonstrated, and it was shown that backpack-typed mobile wireless systems can be utilized through wireless data transmission on a Bluetooth.

Furthermore, a Bluetooth-based mobile system equipped with a global positioning or navigation sensor can detect and monitor environmental radiations. Furthermore, it could be possible to extend to measuring and quantifying gamma rays in the environment, not only harvesting information on the amount of radioactive materials in environments, but also on where the radioactive materials come from, their artificial or physical source, and how or if the gamma radiation is moving around.

5. Patents

KR Patent in progress. Title: Variable radiation detection sensor and wireless communication type radiation monitoring system using the same.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/electronics10222833/s1. Figure S1: Plastic manufacturing processes; Figure S2: Absorption and transmission measurement equipment used in this study; Figure S3: Spectrophotofluorometer with
TCSPC. (a) Overall view of the fluorescence analyzer. (b) Mounting of 30 mm thickness measuring holder. (c) Mounting of 50 mm thick measuring holder; Figure S4: Input data of energy spectrum in an MCNP 6 simulation; Figure S5: Detailed drawing of plastic detector.

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