INNOVATIVE USE OF NUCLEAR DETECTORS FOR SOIL MOISTURE ASSESSMENT IN PHYSICS EDUCATION LABS

[1]M.CHANDRASHEKAR,[2]KIRAN
[12]Students
Department of Physics

ABSTRACT:
In several disciplines, including environmental science, civil engineering, and agriculture, precise soil moisture monitoring is crucial. In order to improve students' comprehension of applied nuclear procedures, this research describes the design and execution of a nuclear physics-based laboratory setting specifically designed for engineering physics instruction. The developed device allows for the non-destructive and real-time measurement of soil water content using neutron scattering and gamma-ray attenuation techniques. To guarantee both operational safety and educational value, the setup includes a safe and economical arrangement of nuclear detectors, shielding materials, and calibration techniques. The usefulness of the system for academic usage is validated by experimental findings that show a consistent connection between detector readings and real soil moisture levels. This laboratory model bridges the gap between theoretical knowledge and practical applications by giving students practical experience in radiation detection, data collection, and environmental assessment. This creative method enhances experimental competences in contemporary engineering courses and promotes interdisciplinary learning.

I. INTRODUCTION

Numerous scientific and engineering fields, such as hydrology, agriculture, geotechnical engineering, and environmental monitoring, depend heavily on soil moisture. Despite their widespread usage, traditional techniques for measuring soil water content, such gravimetric analysis and time-domain reflectometry, can entail intrusive procedures, lengthy processing times, and low accuracy in varied soil settings. Nuclear methods, on the other hand, provide a very sensitive, real-time, and non-destructive substitute for measuring soil moisture content.

Specifically, techniques like neutron scattering and gamma-ray attenuation have worked well for figuring out how much water is in soil by volume. While neutron moderation is directly impacted by the amount of hydrogen in soil, offering an indirect but accurate indicator of moisture, gamma rays predominantly interact with matter via Compton scattering, which fluctuates with variations in soil density and water content. In addition to their scientific value, these nuclear procedures provide a great chance to be included into physics classrooms.

In order to provide students hands-on experience with radiation-based measuring methods, the goal of this project is to develop and execute a nuclear laboratory setup appropriate for engineering physics teaching facilities. Students may get a better grasp of nuclear equipment, radiation-matter interactions, environmental physics, and data analysis methods by using a safe, educationally orientated version of nuclear soil moisture measuring devices.

The conceptual design, component selection, safety concerns, calibration methods, and experimental validation of the suggested lab setup are all covered in this study. This system's incorporation into a school curriculum attempts to close the knowledge gap between theoretical nuclear physics ideas and their practical engineering implementations. Through the creative use of nuclear technology in laboratory instruction, this project ultimately aims to improve experiential learning and cultivate multidisciplinary abilities among engineering and physics students.

II. BASIC THEORY

Any substance, including soil samples, may attenuate gamma rays according to Beer-

Lambert's law. Solids (minerals and organic components), solutes (water), and gases (air) make up the three phases of soil (Figure 1a). Beer-Lambert's law is expressed as follows for a collimated gamma-ray beam interacting with soil [13]:

$$I = I_0 e^{-(\mu_p \rho_p x_p + \mu_w \rho_w x_w + \mu_a \rho_a x_a)}, \quad (1)$$

where the intensity of the incoming beam is denoted by I_0 (counts per second), the beam intensity transmitted through the sample by I (cps) (Figure 1b), the mass attenuation coefficient by μ ($cm^2\ g^{-1}$), the sample density by ρ ($g\ cm^{-3}$), and the sample thickness by x (cm). Particles, water, and air are denoted by the subscripts p, w, and a, respectively.

Because the density and mass attenuation coefficient of air are far lower than those of solids and liquids, the interaction of gamma rays with air is often disregarded. Equation (1) may thus be reduced to:

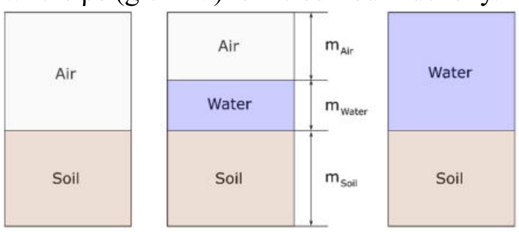
$$I = I_0 e^{-(\mu_p \rho_p x_p + \mu_w \rho_w x_w)}. \quad (2)$$

As is well known, the water content of soil may be determined using either the volumetric (θ: $cm^3\ cm^{-3}$) or gravimetric (G: $g\ g^{-1}$) methods [5]. While the volumetric water content is determined by the water volume (V_w: cm^3) per unit of soil volume (V_s: cm^3) (Equation (4)), and is often reported as a percentage [4], the gravimetric water content is represented by the water mass (m_w: g) per unit of dry soil mass (m_s: g) (Equation (3)):

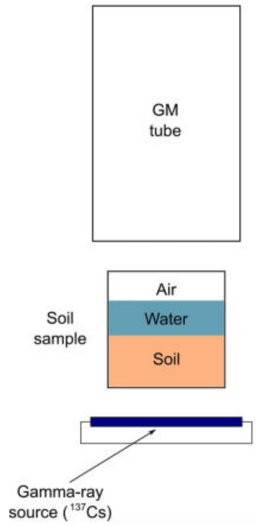
$$G = \frac{m_w}{m_s},$$

$$\theta = \frac{V_w}{V_s} = \frac{\rho_s}{\rho_w} G,$$

where ρ_s ($g\ cm^{-3}$) is the soil bulk density.



(a)



(b)

Figure 1. Schematic drawing showing (a) the soil as a three-phase system and (b) the experimental gamma-ray attenuation geometry (the figure is only schematic and not to scale). GM: Geiger-Müller detector. The symbol m stands for mass.

Based on the concepts of soil bulk and particle densities [1], Equation (2) becomes:

$$I = I_0 e^{-x(\mu_p \rho_s + \mu_w \theta \rho_w)}. \quad (5)$$

Equation (5) is utilized for measuring, for example, the bulk density when the soil is dry ($\theta = 0\ cm^3\ cm^{-3}$) (Figure 1a—left):

$$\rho_s = \frac{1}{x\mu_p} \ln\left(\frac{I_0}{I}\right) \quad (6)$$

If the soil is moist (Figure 1a—center and right), Equation (5) can also be employed for monitoring the sample water content:

$$\theta = \frac{1}{x\mu_w\rho_w}\left[\ln\left(\frac{I_0}{I}\right) - x\mu_p\rho_s\right] \quad (7)$$

III. MATERIALS AND METHODS

The water content of the examined soil samples was determined using a PASCO kit [17] (Figure 2). A soil sample, source holders (sample + GM + radioactive source), a Geiger-Müller (GM) detector (reference number SN-7970-A), a radiation counter (high voltage source (0 to 1200 V) + timer + counter—reference number SN-7907), and a ^{137}Cs radioactive source (reference number SN-7972A) make up the setup (see Supplementary Figure S1). The kit's Caesium-137 source is a sealed plastic pellet with a diameter of 2.5 cm and an activity of around 3.4 µCi. The energy of the gamma-ray photons released by this radioactive source is about 0.662 MeV. It has a half-life of about 30.2 years. The radioactive source's reported uncertainty is ±15%, as per the manufacturer's requirements. It is important to note that the kit maker states that these radioactive sources are USNRC License Exempt (US). Three 137Cs sources were stacked one atop the other in the suggested experiment in order to boost the photon flux that passed through the samples. Consequently, the source assembly's overall activity was around 10.2 µCi [18].

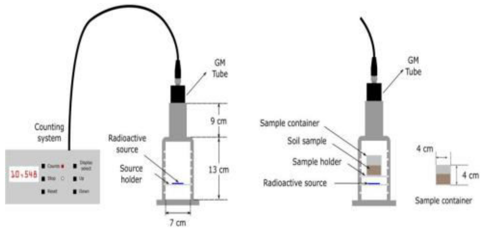


Figure 2. Schematic drawing of the Intermediate Nuclear Laboratory Setup.

The GM detector used in the experiment is composed of mica (2 mg cm−2) and has a 35 mm diameter window. It is built to provide for high counting efficiency for radioactive sources with low activity. The tube has a dead time of around 200 µs. 920 V was chosen as the operating voltage to power the GM. The counting plateau of the GM detector, which ranged from 760 to 980 V, was established in an earlier experiment. The holder, which has slots 1.0 cm apart, allowed the teaching instructor to rapidly and easily change the placements of the radioactive sources and soil samples for the experiment (Figure 2 and see Supplementary Figure S1).

The classroom teacher is permitted to touch the radioactive sources due to worries about radiation safety. It is an additional worry, however, since the radioactive sources in this kind of system are not highly active. During the measurements, lead plates that are about 3 mm thick may be positioned around the radioactive source to further enhance this protection. Undergraduate students are positioned safely away from the experimental equipment (radioactive source + GM detector + sample) and are solely in charge of operating the electronics that count incident and transmitted gammaray photons that reach the GM detector during these experiments. Furthermore, a tiny aperture in the sealed radioactive source allows photons to be emitted upward perpendicular to the students' location.

A radiation counter system (PASCO—Spectech ST-360 Counter) that included a timer, preset counter, digital ratemeter, computer interface, and battery power for field usage was used to record the counts. The time intervals used for each measurement were 5 × 102 s (about 8 min) for sandy clay loam and clay soils and 103 s (approximately 17 min) for silt loam and heavy clay soils. The measurements' (total counts collected) obtained uncertainty for these time periods was 1% or less. Additionally, this time frame was chosen to allow for experimental measures in two or three 50-minute lectures. For the experimental measurements, soil samples with four distinct particle size fractions—Silt Loam—SiLo, Heavy Clay—HeCa, Sandy Clay Loam—SaCLo, and Clay—Cla—were used (Figure 3). For each soil, around 100 g were sieved at 2 mm (10 Mesh). The goal of this process was to get as many uniform soil samples as feasible. The soil samples were oven-dried (air-forced circulation) for 24 hours at 105 °C prior to sifting.

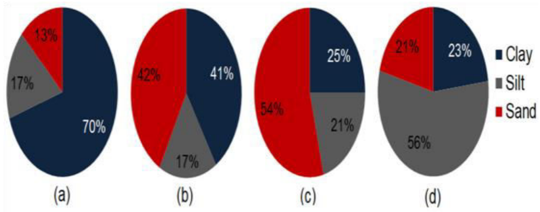


Figure 3. Particle size fractions of the soils studied: (a) Heavy Clay (HeCa), (b) Clay (Cla), (c) Sandy Clay Loam (SaCLo), and (d) Silt Loam (SiLo).

Following that, the soil samples were put in 3.25 cm-diameter, 35 cm3-volume cylindrical plastic containers (see Supplementary Table S1). Every soil was meticulously positioned inside the experiment's pots. The samples were standardised by filling the sample containers until the gamma-ray photons from the radioactive source passed the sample thickness (soil depth) of around 2.65 to 2.70 cm (see Supplementary Table S1). Within each container, this thickness corresponded to a soil volume of around 25 cm3. The dirt within the container was levelled using a pestle that had the same internal diameter as the container (see Supplementary Figure S1). Following container filling, the gravimetric technique was used to assess the samples' soil bulk density (Table 1).:

$$\rho_s = \frac{m_s}{V_s}. \qquad (8)$$

Table 1. Soil bulk density (ρs), soil particle density (ρp), and volume of pores (Vpor) of the contrasting soils studied.

Soil/Properties	$?_s$ (g cm^{-3})
HeCa	1.08
Cla	1.20
SaCLo	1.10
SiLo	1.03

Heavy Clay (HeCa), Clay (Cla), Sandy Clay Loam (SaCLo), and Silt Loam (SiLo). Equation (8) was used to compute the bulk density of the soil, and Equation (10), to determine the volume of pores.

Equations (9) and (10), respectively, were used to determine the soil samples' porosity (ϕ: cm3 cm−3) and pore volume (Vpor: cm3). Five different θ were then chosen to moisten the samples (see Supplementary Table S2). Vpor was divided by five to determine the five distinct volumes of water that would be gradually added to the samples. The sample was soaked by the final amount of water applied (Table 1). [5].

$$\varphi = 1 - \frac{\rho_s}{\rho_p}, \qquad (9)$$

$$V_{por} = V_s\varphi, \qquad (10)$$

where the gas pycnometer technique was used to estimate the particle density (ρp: g cm−3) of the contrasted soils (see Supplementary Table S1). [19]. Without this measurement, the soil particle density is often assumed to be 2.65 g cm−3.

To conduct the studies, the soil sample (soil + container) was positioned directly above the radioactive source (sealed plastic pellet) at various moisture conditions. A pipette was used to regulate the amount of water that was to be introduced to the soil. A precision balance (Gehara AG200, 10−4 g accuracy) was used to measure the mass. The detector and the radioactive source were about 6.5 cm apart. The sample top and the detector window were separated by a 0.050 mm thick aluminium plate (provided by PASCO) to avoid the detection of beta particles (energy of about 0.512 MeV) from the 137Cs radioactive source.

We assessed the photon intensity transmitted through the dry soil samples (I) and the photons transmitted through the wet soil samples (I0) before determining the soil water content (see Supplementary Table S3). The volumetric water content of the sample might be determined using Equation (11):

$$\frac{1}{x\mu_w\rho_w} \quad I_{\theta} . \qquad (11)$$

0.998 g cm−3 was the water density value used in the computations. The water mass attenuation coefficient for photons from 137Cs is about 0.0767 cm2 g−1 [20], based on the literature.

A flow chart outlining the fundamental procedures used for the experimental θ measurements is shown in Figure 4.

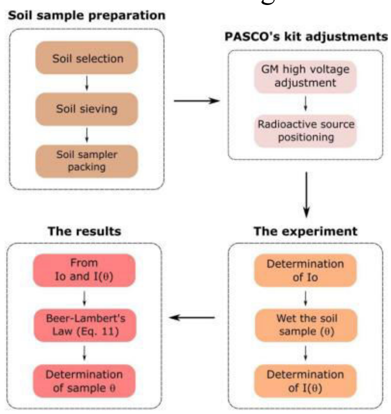


Figure 4 shows the flow chart of the procedures used to measure the soil water content (θ) using the streamlined gamma-ray attenuation technique. Geiger-Müller detector, or GM. I0: The incident photon beam's intensity. I: The photon beam's intensity during transmission.

IV. RESULTS AND DISCUSSION

For every soil type examined, the graphs of the number of photons transmitted (I) as a function of the samples' θ exhibited a linear behaviour (R ranging from -0.95 to -0.98) (Figure 5). The extended counting period used for these specific soil samples was the cause of the higher count values seen for HeCa and SiLo.

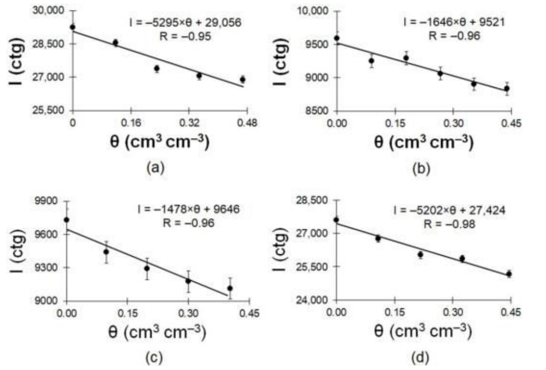


Figure 5. Transmitted gamma-ray photons (I) as a function of the volumetric water content (θ) for the soils: (a) Heavy Clay (HeCa), (b) Clay (Cla), (c) Sandy Clay Loam (SaCLo), and (d) Silt Loam (SiLo). The error bars represent the counting (ctg) statistics. θ was kept constant for each counting step.

The variations in the compositions of the dry soil samples are linked to the variations in photon counts (θ = 0 cm3 cm−3). For instance, the mineralogy and chemical composition of the soil (mostly the oxide content) would affect the particle density and other soil characteristics that are directly connected to radiation attenuation (Equation (2)). The attenuation coefficient is another metric that is impacted by the chemical makeup of the soil [21–23]. The photoelectric effect, whose cross-section is proportional to Z4−5 and inversely proportional to the photon energy (E−3 when <500 keV), is the primary factor influencing the attenuation coefficient for low-energy photons (<100 keV) [24,25]. The incoherent scattering affects the photon interaction and, in turn, the attenuation coefficient, whose cross-section has a Z dependency, for the intermediate energy area (c. 100 keV to c. 10 MeV) [26,27]. The most significant step in the attenuation of the radiation linked to the Z2 dependency of its cross-section for high-energy photons (E > 10 MeV) is pair creation. The primary factor affecting the photon (137Cs) interaction and the attenuation coefficient in our investigation was incoherent scattering. For instance, Camargo et al. [26] showed that for the photon energy of 137Cs, the overall attenuation coefficient is entirely determined by the incoherent scattering (>99%) when dealing with tropical/subtropical soils that have different main oxide (SiO2, Al2O3, Fe2O3, TiO2) compositions. Additionally, as previously mentioned, these writers primarily linked the Z dependency on the partial cross-sections to the dominance of each of the partial effects (photoelectric effect, incoherent scattering, and pair creation).

Only by knowing the photons transmitted by the sample can θ (interpolation) be predicted using the equations derived from fitting the experimental data (Figure 5). Two care must be taken for this interpolation, though: the sample water volume must not be more than the maximum volume required for the sample to be saturated, and an appropriate calibration equation must be found for each kind of soil. Using Equation (11) (Table 2), we computed the total porosity of the examined soils using the simplified GRA technique based on the θ values acquired at saturation. When compared to the conventional approach, we discovered total porosity variations ranging from c. 7.8% (SiLo) to c. 18.2% (SaCLo) (Equation (9)).

Table 2: Total porosity (ϕ) as determined by simplified gamma-ray attenuation (GRA) and conventional (TRA) techniques.

Soil/Methods	TRA	GRA
	? (cm^3 cm^{-3})	
HeCa	0.591	0.515
Cla	0.445	0.377
SaCLo	0.505	0.413
SiLo	0.540	0.582

Heavy Clay (HeCa), Clay (Cla), Sandy Clay Loam (SaCLo), and Silt Loam (SiLo). Equation (9) was used to calculate the total porosity of the conventional soil, and Equation (11) was used to calculate the porosity based on radiation attenuation.

The overall porosity findings might be impacted by the properties of each soil and the existence of trapped air bubbles during the saturation process. Therefore, it is important to apply caution when estimating θ at saturation as the entire porosity. The experimental equipment used by the radioactive source is not collimated, and there is no single-channel analyser to identify the photopeak area associated with the photons released by Ca. This is another factor contributing to the observed inconsistencies. Consequently, the GM detector detects both transmitted and scattered photons [27, 28]. Due to this circumstance, Equation (11), which need to contain a correction parameter (buildup factor) and was not discussed in our work [29,30], has limitations when it comes to keeping the analysis as straightforward as feasible.

Upon examining the total porosity data (Table 2—traditional technique) pertaining to the soil particles (Figure 3), we find that, generally speaking, soils with a greater clay content (HeCa) have higher total porosities. Conversely, the overall porosity decreases when sand particles (SaCLo) predominate. In contrast to clayey soils, soils with a greater sand content are often denser and, as a result, less porous (low porosities) [1,4]. Therefore, our findings seem to be in line with expectations. Lastly, this specific soil feature is influenced by the silt concentration in an intermediate way (between clay and sand).

When the θ values from the conventional and simplified GRA techniques are compared, Figure 6 demonstrates that there was sufficient agreement between the findings, with the exception of HeCa (R = 0.90). Clay and silt loam soils had the best results, with measurements that were nearer the 1:1 line. The observed variations in the approaches may be explained by a few factors. One of these is the simplicity of the electronic system (i.e., no channel analyser) used to detect the gamma-rays using the nuclear method; that is, the PASCO kit is primarily intended for educational purposes, making it more limited and simpler than those used in applied nuclear physics research [18]. For instance, the basic GRA system can detect scattered photons, which is something that is minimised in systems where the photon energy to be analysed is selectable. Additionally, as previously stated, the usage of Equation (11), is limited by the detection and counting of scattered photons. Lastly, the detector type used (GM) is based on the gas ionisation process, which is less effective at detecting higher-energy gamma-ray photons than, say, solid scintillation detectors, which are often used in research systems [31].

The approach based on gamma-ray attenuation is well established and is utilised today, despite the fact that several different techniques are used in θ monitoring [12,32–36]. For high-activity radioactive sources, this nuclear approach allows for quick and precise measurements of θ [20]. Additionally, this flexible approach enables measurements in both laboratory and outdoor settings [32, 33]. As a teaching exercise, our research suggested using small-volume disturbed soil samples to apply the simplified nuclear system to laboratory observations of θ. These samples were idealised in light of the Intermediate Nuclear Laboratory System's constraints [17], including the detector's size and type, the sample holder's dimensions, and the radioactive source's low activity (a radiological protection concern for instructional operations). However, the main goal of our work was to demonstrate that even the most basic GRA system produces good results and may be used to investigate ideas pertaining to the method itself (physical principles) as well as the principles of operation of the electronics and gamma-ray detector.

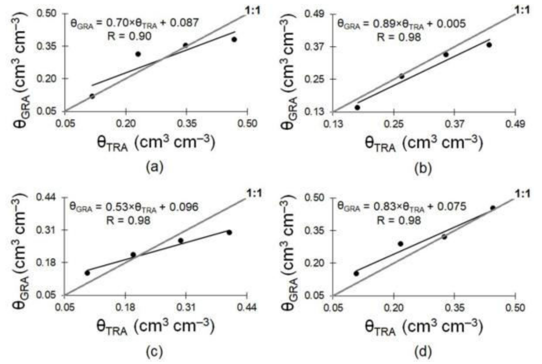


Figure 6. Comparison of the soil water content (θ) evaluated by the traditional (θTRA—Equation (4)) and simplified gamma-ray attenuation (θGRA—Equation (11)) methods (1:1 line) for the contrasting soils: (a) Heavy Clay (HeCa), (b) Clay (Cla), (c) Sandy Clay Loam (SaCLo), and (d) Silt Loam (SiLo). The error bars for θGRA are not presented in the graphs due to their magnitudes (varied from 0.0002 to 0.0016 cm3 cm−3). θTRA was kept constant during the experimental procedure.

V. CONCLUSIONS

An important breakthrough in experiential learning in engineering physics education is the creation of a nuclear laboratory setup for determining the water content of soil. The device offers a trustworthy, real-time, non-invasive approach for determining soil moisture by using gamma-ray attenuation and neutron scattering techniques. This method is both scientifically sound and beneficial for teaching.

According to this study, incorporating nuclear measurement concepts into instructional labs improves students' comprehension of radiation-matter interactions and environmental applications while also fortifying their instrumentation, data interpretation, and safety procedures skills. The outcomes of the experimental trials validate the system's appropriateness for usage in academic settings by confirming its accuracy and repeatability.

Additionally, the setup's economical and secure design guarantees its use in educational establishments, even those with little funding. The suggested methodology closes the knowledge gap between theory and practice by providing students with practical experience with applied nuclear technology in the context of environmental engineering.

To sum up, this cutting-edge laboratory method fosters interdisciplinary learning, stimulates scientific curiosity, and gets students ready for postsecondary study or jobs in geotechnical engineering, nuclear science, and environmental monitoring. To further improve the educational experience, future improvements may include automation, digital integration, and larger experimental modules.

REFERENCES

1. Hillel, D. Environmental Soil Physics; Academic Press: San Diego, CA, USA, 1998.
2. Pimentel, D.; Berger, B.; Filiberto, D.; Newton, M.; Wolfe, B.; Karabinakis, E.; Clark, S.; Poon, E.; Abbett, E.; Nandagopal, S. Water Resources: Agricultural and Environmental Issues. BioScience 2004, 54, 909–918. [CrossRef]
3. Tarawally, M.A.; Medina, H.; Frómeta, M.E.; Alberto Itza, C. Field Compaction at Different Soil-Water Status: Effects on Pore Size Distribution and Soil Water Characteristics of a Rhodic Ferralsol in Western Cuba. Soil Tillage Res. 2004, 76, 95–103. [CrossRef]
4. Lal, R.; Shukla, M.K. Principles of Soil Physics; Marcel Dekker, Inc.: New York, NY, USA, 2004.
5. Reichardt, K.; Timm, L.C. Soil, Plant and Atmosphere: Concepts, Processes and Applications; Springer Nature: Cham, Switzerland, 2020.

6. Pires, L.F.; Cássaro, F.A.M.; Correchel, V. Use of Nuclear Techniques in Soil Science: A Literature Review of the Brazilian Contribution. Rev. Bras. Ci. Solo 2021, 45, e0210089. [CrossRef]
7. Wang, J.; Watts, D.B.; Meng, Q.; Ma, F.; Zhang, Q.; Zhang, P.; Way, T.R. Influence of Soil Wetting and Drying Cycles on Soil Detachment. AgriEngineering 2022, 4, 533–543. [CrossRef]
8. Dapla, P.; Hriník, D.; Hrabovský, A.; Simkovic, I.; Zarnovican, H.; Sekucia, F.; Kollár, J. The Impact of Land-Use on the Hierarchical Pore Size Distribution and Water Retention Properties in Loamy Soils. Water 2020, 12, 339.
9. Buckinghan, E. Studies on the Movement of Soil Moisture; Bulletin, No. 38; United States Department of Agriculture, Bureau of Soil: Washington, DC, USA, 1907.
10. Celik, N.; Altin, D.; Cevik, U. A New Approach for Determination of Volumetric Water Content in Soil Samples by Gamma-Ray Transmission. Water Air Soil Pollut. 2016, 227, 207. [CrossRef]
11. Schaap, M.G.; Leij, F.J. Using Neural Networks to Predict Soil Water Retention and Soil Hydraulic Conductivity. Soil Tillage Res. 1998, 47, 37–42. [CrossRef]
12. Demir, D.; Ün, A.; Özgül, M.; Sahin, Y. Determination of Photon Attenuation Coefficient, Porosity and Field Capacity of Soil by Gamma-Ray Transmission for 60, 356 and 662 keV Gamma Rays. Appl Radiat Isot. 2008, 66, 1834–1837. [CrossRef]
13. Filiz Baytas, A.; Akbal, S. Determination of Soil Parameters by Gamma-Ray Transmission. Radiat Meas. 2002, 35, 17–21. [CrossRef]
14. Oliveira, J.C.M.; Appoloni, C.R.; Coimbra, M.M.; Reichardt, K.; Bacchi, O.O.S.; Ferraz, E.; Silva, S.C.; Galvão Filho, W. Soil Structure Evaluated by Gamma-Ray Attenuation. Soil Tillage Res. 1998, 48, 127–133. [CrossRef]
15. Naime, J.M.; Vaz, C.M.P.; Macedo, A. Automated Soil Particle Size Analyzer based on Gamma-Ray Attenuation. Comput. Electron. Agric. 2001, 31, 295–304. [CrossRef]
16. Elsafi, M.; Koraim, Y.; Almurayshid, M.; Almasoud, F.I.; Sayyed, M.I.; Saleh, I.H. Investigation of Photon Radiation Attenuation Capability of Different Clay Materials. Materials 2021, 14, 6702. [CrossRef]
17. PASCO. Available online: https://www.pasco.com/products/lab-apparatus/atomic-and-nuclear/sn-7900#desc-panel (accessed on 23 March 2023).
18. Pires, L.F.; Cássaro, F.A.M.; Tech, L.; Pereira, L.A.A.; de Oliveira, J.A.T. Gamma Ray Attenuation for Determining Soil Density: Laboratory Experiments for Environmental Physics and Engineering Courses. Rev. Bras. Ens. Fis. 2020, 42, e20190340. [CrossRef]
19. Amoozegar, A.; Heitman, J.L.; Kranz, C.N. Comparison of soil particle density determined by a gas pycnometer using helium, nitrogen, and air. Soil Sci. Soc. Am. J. 2023, 87, 1–12. [CrossRef]
20. Ferraz, E.S.B.; Mansell, R.S. Determining Water Content and Bulk Density of Soil by Gamma-Ray Attenuation Methods; TechnicalBulletin No. 807; University of Florida: Gainesville, FL, USA, 1979.