Establishing a Nuclear Laboratory for Measuring Soil Water Content in Engineering Physics Teaching Labs

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Abstract:

The soil water content (θ) is a crucial soil parameter that is assessed in many geological, engineering, soil, and environmental science investigations. For instance, θ affects the evaluation of soil aeration status, groundwater recharge, hydraulic conductivity, and strength. Many soil processes depend on the measurement of θ for monitoring and control. The gammaray attenuation (GRA) methodology is a rapid and non-destructive way to measure μ in soils with radically diverse compositions. However, GRA is rarely covered in lab physics lectures. A proposal is made for an experiment that uses a teaching GRA equipment to measure θ. The experimental setup consisted of a radioactive source with a 37Cs decay, a radiation counter, and a Geiger-Müller detector. Four distinct soil sample granulometric compositions were investigated. The intensity of the transmitted gamma-ray photon and Strong linear correlations between θ were discovered, with correlation values ranging from -0.95 to -0.98. The porosity of the soil varied between the GRA and traditional methods, ranging from roughly 7.8% to 18.2%. Additionally, a strong linear correlation between the GRA and the traditional gravimetric method of determining θ was observed, with correlation coefficients ranging from 0.90 to 0.98. It was confirmed that the teaching GRA equipment was successful in measuring θ. The tool also makes it possible for undergraduate students from a range of topic areas to learn about some important aspects of studying modern physics.

Keywords: attenuation coefficient, 137Cs gamma-ray photons, soil aggregates, soil granulometry, and soil porosity.

1 . Introduction

Water is a necessary component of life. Capillarity in the soil skeleton's pores stores and holds it for plants [1]. An indicator that is frequently linked to the upkeep and establishment of irrigated crops is the soil water content (θ), which can be reported as mass or volume percentages. Given that 70% of the freshwater utilized globally is used in agriculture, the topic of rational water use in this sector is extremely important [2]. Regretfully, half of this water is squandered since it is used improperly in various agricultural techniques that have been created globally. Furthermore, the plant must have access to the water in the soil in order for it to be absorbed [3].

When all of the pore space in the soil is filled with water, the soil is said to be saturated [4]. Conversely, when all of the soil's pore space is filled with air, the soil is said to be dry. The soil is considered moist if it falls between these two extremes. The research currently in publication indicates that there are various approaches to calculating θ [1]. Determining the mass or volume of water contained in the sample at the moment of analysis is the foundation of the conventional (standard) approach [5]. Other techniques to measure θ rely on how particles or photons interact with the sample. These include techniques based on gamma radiation attenuation or rapid neutron moderation [6]. Analyzing laboratory samples is one way to determine the water content of soil or under field conditions, depending on the study carried out.

The idea of soil water content is essential for figuring out the physical-hydric behavior of the soil in applied physics to engineering undergraduate courses [7, 8]. Determining θ is also essential for assessing hydraulic conductivity and the soil water retention curve [9–11]. Undergraduate engineering students rarely have access to equipment that measures θ based on the interaction of radiation with matter. These kinds of instruments are typically limited to graduate research activities and found in organizations that do applied nuclear method research [12–16].

As an alternative to the conventional gamma-ray attenuation (GRA) systems typically used in soil characteristics assessments, this study proposes the use of a simpler GRA system created for educational purposes [6,10,12–16]. A Geiger-Müller detector, low-activity radioactive sources, and a photon counting device make up the simplified setup. As far as we are aware, no publications examining GRA systems for θ measurements targeted at undergraduate engineering students exist. Therefore, our study suggests a method for using a simplified GRA system to monitor θ in soil samples under various moisture circumstances. Additionally, the proposed method provides a thorough explanation of the measurements' theoretical components, which can help instructors carry out instructional activities utilizing this information.

The findings obtained and displayed here show that the suggested method is highly effective in figuring out the θ of soil samples with different granulometries. However, the current conventional GRA systems are not meant to be replaced by this study. Our method simply comprises of an excellent substitute for instructional tasks that allow for a satisfactory exploration of the ideas of soil water content, soil pore space, radiation interaction with matter, and radiation generation and detection.

2. Basic Theory

Any material, including soil samples, can attenuate gamma rays according to Beer-Lambert's law. Solids (minerals and organic components), solutes (water), and gasses (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]:

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

where the intensity of the incident 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 frequently disregarded. Equation (1) can therefore be reduced to:

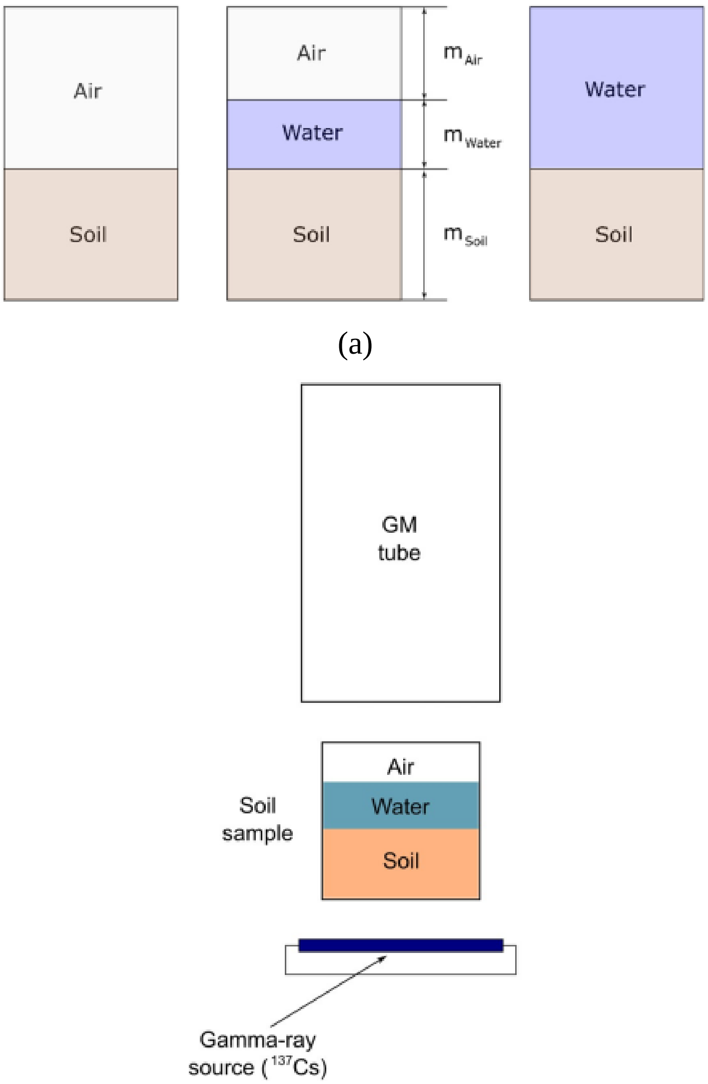
$$I = I_0 \, e^{-(\mu_p \rho_p x_p + \mu_w \rho_w x_w)}. \qquad (2)$$

As is well known, the water content of soil can 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 typically reported as a percentage [4], the gravimetric water content is represented by the water mass (mw: g) per unit of dry soil mass (ms: g) (Equation (3)):

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

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

where ρs (g cm−3) is the soil bulk density.



(a)

(b)

Figure 1. The picture is merely conceptual and not to scale, but it depicts (a) the soil as a three-phase system and (b) the experimental gamma-ray attenuation geometry. Geiger-Müller detector, or GM. The letter m represents mass.

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

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

Equation (5) is utilized for measuring, for example, the bulk density when the soil is dry (θ = 0 cm3 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:

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

3. Materials and Methods

The water content of the examined soil samples was ascertained 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 137Cs 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 about 3.4 µCi. The energy of the gamma-ray photons released by this radioactive source is approximately 0.662 MeV. It has a half-life of approximately 30.2 years. The radioactive source's reported uncertainty is ±15%, as per the manufacturer's requirements. Noteworthy is the fact that these radioactive sources are USNRC License Exempt (US) according to the kit manufacturer. In the proposed experiment, three 137Cs sources were pilled (set one above the other) to increase the flux of photons transmitted through the samples. Thus, the total activity of the source assembly was c. 10.2 µCi [18].

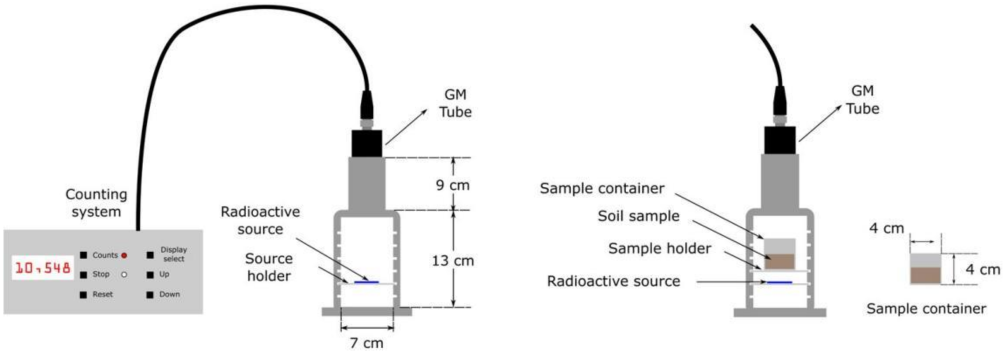


Figure 2. Schematic drawing of the Intermediate Nuclear Laboratory Setup.

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 good counting efficiency for radioactive sources with low activity. The tube has a dead time of about 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 instructor is permitted to touch the radioactive sources due to worries about radiation protection. It is an additional worry, though, because the radioactive sources in this type of system are not highly active. During the measurements, lead plates that are about 3 mm thick can 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 only 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' position.

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 chosen 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 to three 50-minute lectures.

Soil samples with four contrasting particle size fractions, identified as Silt Loam—SiLo,

For the experimental measurements, heavy clay (HeCa), sandy clay loam (SaCLo), and clay (Cla) were chosen (Figure 3). To create as homogeneous soil samples as possible, 100 g of each soil was sieved at 2 mm (10 Mesh). Prior to sieving, the soil samples were oven-dried (air-forced circulation) for 24 hours at 105 ◦C.

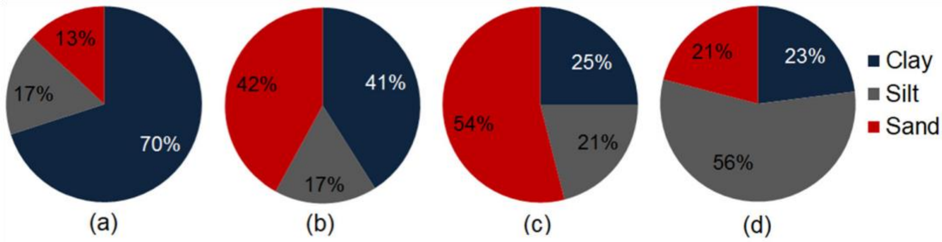


Figure 3. Particle size fractions of the soils studied: (a) Heavy Clay (HeCa), (b) Clay (Cla), (c) Sandy Clay Loam (SaCLo), and (d) Silt Loam (SiLo).

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 within the experiment's pots. The samples were standardized by filling the sample containers until the gamma-ray photons from the radioactive source crossed the sample thickness (soil depth) of roughly 2.65 to 2.70 cm (see Supplementary Table S1). Within each container, this thickness corresponded to a soil volume of roughly 25 cm3. The soil inside the container was leveled using a pestle that had the same internal diameter as the container (see Supplementary Figure S1). Following container filling, the gravimetric method was used to assess the samples' soil bulk density (Table 1):

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

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)	? p (g cm−3)	Vpor (cm3 cm−
HeCa	1.08	2.63	14.77
Cla	1.20	2.16	11.13
SaCLo	1.10	2.22	12.62
SiLo	1.03	2.25	13.50

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].

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

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

where the gas pycnometer method was used to quantify the particle density (ρp: g cm−3) of the contrasted soils (see Supplementary Table S1) [19]. Without this measurement, the soil particle density is typically taken 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. Between the sample top and the detector window, a 0.050 mm thick aluminum plate (provided by PASCO) was positioned to block the detection of beta particles (energy of approximately 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 moisture soil samples (Iθ) before determining the soil water content (see Supplementary Table S3). The volumetric water content of the sample might be ascertained using Equation (11):

$$\frac{1}{x\mu_w\rho_w} \ln \frac{I}{I_\theta} \quad (11)$$

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

Figure 4 shows a flow chart containing the basic steps followed for the experimental θ measurements.

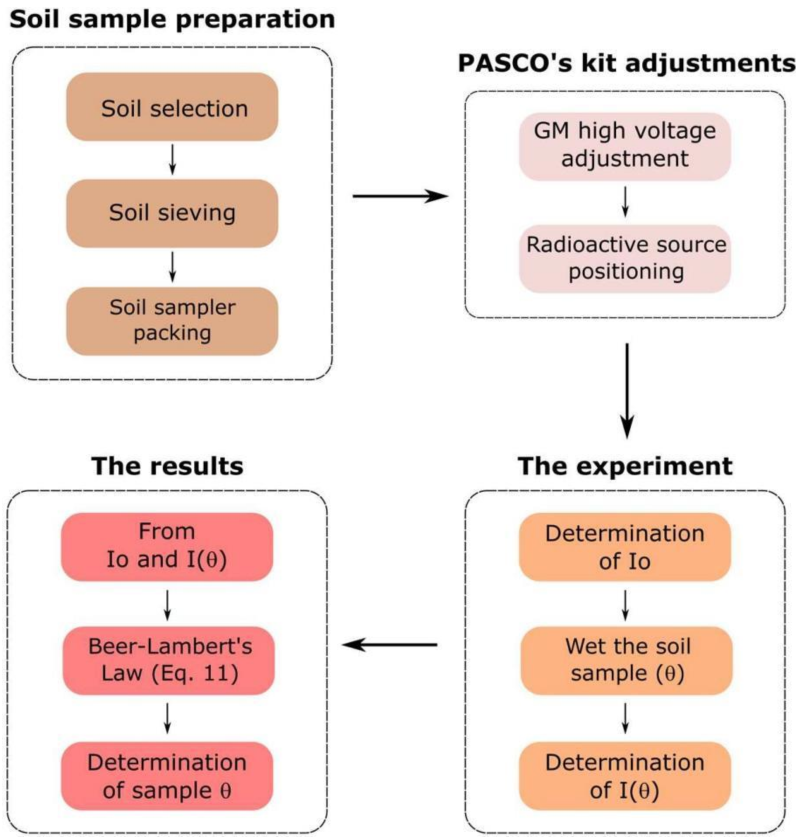


Figure 4. Flow chart of the steps followed for the soil water content (θ) measurement using the simplified gamma-ray attenuation method. GM: Geiger-Müller detector. I0: Intensity of the incident photon beam. I: Intensity of the transmitted photon beam.

4. 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 pattern (R ranging from -0.95 to -0.98) (Figure 5). The longer counting period used for these specific soil samples was the cause of the higher count values seen for HeCa and SiLo.

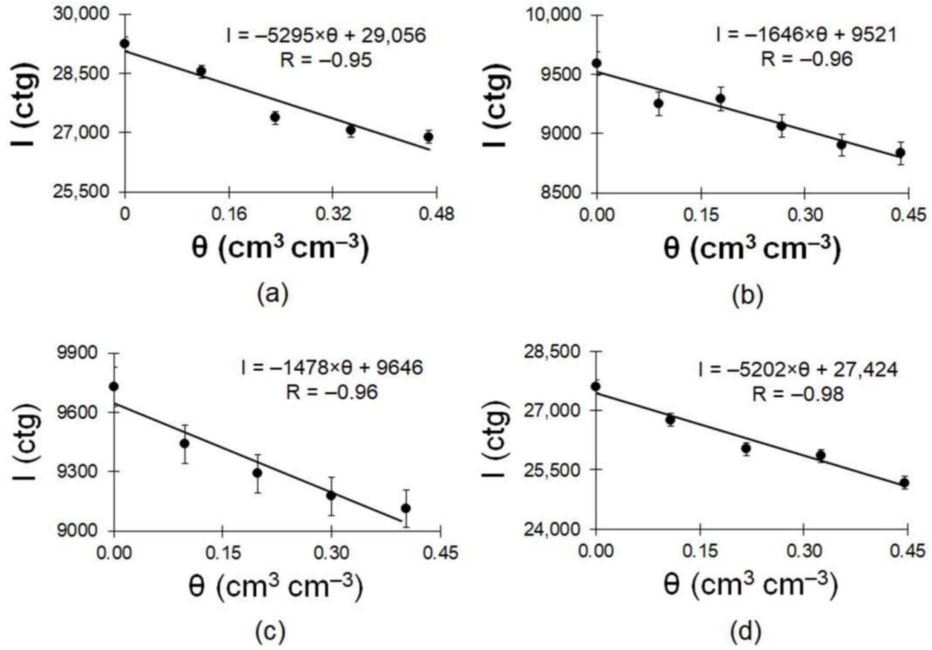


Figure 5. Transmitted gamma-ray photons (I) as a function of the volumetric water content (θ) for the soils: (a) Heavy Clay (HeCa), (b) Clay (Cla), (c) Sandy Clay Loam (SaCLo), and (d) Silt Loam (SiLo). The error bars represent the counting (ctg) statistics. θ was kept constant for each counting step.

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 related 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 photon interaction is impacted by the incoherent scattering in the intermediate energy area (c. 100 keV to c. 10 MeV), and as a result, the attenuation coefficient, with a Z-dependent cross-section [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 working with tropical/subtropical soils that have different major 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 greater than the maximum volume required for the sample to be saturated, and an appropriate calibration equation must be found for each type 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. In comparison to the conventional approach, we discovered total porosity variations ranging from approximately 7.8% (SiLo) to approximately 18.2% (SaCLo) (Equation (9)).

Table 2. Total porosity (ϕ) obtained by the traditional (TRA) and simplified gamma-ray attenuation (GRA) methods.

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 traditional soil, and Equation (11) was used to calculate the porosity based on radiation attenuation. The overall porosity results could 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 total porosity. The experimental equipment used by the radioactive source is not collimated, and there is no single-channel analyzer to identify the photopeak region 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]. This fact results in disadvantages when using . This fact causes drawbacks in using Equation (11), which should have a correction parameter (buildup factor), This, in order to keep the analysis as straightforward as feasible, was not addressed in our study [29, 30]. Upon examining the total porosity data (Table 2—traditional method) pertaining to the soil particles (Figure 3), we find that, generally speaking, soils with a higher 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 higher sand content are typically denser and, as a result, less porous (low porosities) [1,4]. Therefore, our findings appear to be in line with expectations. Lastly, this specific soil feature is influenced by the silt content in an intermediate way (between clay and sand).

When the θ values from the conventional and simplified GRA methods are compared, Figure 6 demonstrates that there was sufficient agreement between the results, with the exception of HeCa (R = 0.90). Clay and silt loam soils showed the best results, with measurements that were nearer the 1:1 line. The observed variations in the approaches can be explained by a few factors. One of these is the simplicity of the electronic system (i.e., no channel analyzer) 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 simpler GRA system is capable of detecting dispersed photons; this is something that is minimized in systems in which the photon energy to be analyzed can be chosen. Furthermore, the detection and counting of scattered photons limit the use of Equation (11), as mentioned before. Finally, the type of detector utilized (GM) is based on the gas ionization mechanism, which has a lower efficiency in detecting gamma-ray photons of higher energies when compared, for instance, to solid scintillation detectors that are usually employed in research systems [31].

The technique based on gamma-ray attenuation is well established and still utilized 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 study suggested using small-volume disturbed soil samples to apply the simplified nuclear system to laboratory observations of θ. These samples were idealized 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, our study’s core idea was to show that even the simplified GRA system gives satisfactory results and might be employed to explore concepts related to the technique itself (physical principles) and the principles of operation of the electronics and gamma-ray detector.

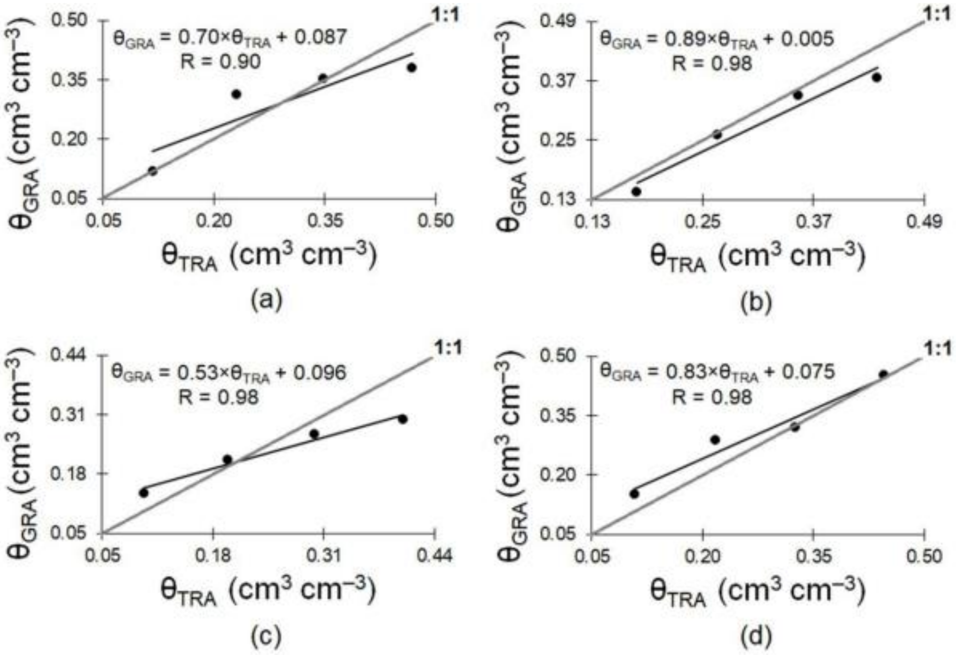


Figure 6. Comparison of the soil water content (θ) for the following different soils: (a) Heavy Clay (HeCa), (b) Clay (Cla), (c) Sandy Clay Loam (SaCLo), and (d) Silt Loam (SiLo) using the conventional (θTRA—Equation (4)) and simplified gamma-ray attenuation (θGRA—Equation (11) techniques (1:1 line). The plots do not display the θGRA error bars because of their magnitudes, which range from 0.0002 to 0.0016 cm3 cm−3. θTRA remained constant throughout the experiment.

5.Conclusions

The present study shown that a simplified gamma-ray attenuation device to measure θ is feasible. Additionally, we evaluated the samples' total porosity by calculating θ at saturation using the Beer-Lambert formula. The nuclear method for θ monitoring had a different setup and was significantly more limited than the traditional radiation attenuation-based methods. As stated earlier, we employed a gas-filled (GM) tube detector, low-activity radioactive sources, a non-collimated system, and basic electronics for the measurements. Therefore, the main cause of the differences between the GRA methodology and the conventional method of θ evaluation may be the limitations of the reduced nuclear system. However, despite these limitations, we were still able to determine θ and the general porosity of soil samples using employing the previously reported nuclear method to different textural fractions. Changes in soil composition (chemical composition and grain sizes) can explain why different calibrations are required for θ estimation based on nuclear approaches. Nonetheless, the calibration procedure can be seen as an initial educational activity that illustrates the relationship between variations in the photon counts and shifts in the soil's composition. We also said that the counting time needs to be improved in order to increase the intrinsic sensitivity of the method related to the GRA approach. As future developments, we suggest using radioactive sources (such 133Ba or 241Am) that emit less powerful gamma-ray photons and collimating the photon beam before it enters the GM tube. As a whole, our findings demonstrated that teaching undergraduate students about radiation detection, nuclear electronics, gamma-ray attenuation, and the analysis of particular soil properties could be made more interesting by using the simplified nuclear system and approach.

Additional Resources: https://www.mdpi.com/article/10.3390/agriengineering5020068/s1 contains the supporting data. Figure S1 shows a picture of the experimental setup used to determine the soil's moisture content. The parameters utilized to determine the water content of soil using the gamma-ray attenuation method are listed in Table S1. Table S2. During experimental soil moisture measurements, the gamma-ray attenuation method is used to determine the gravimetric water content (G). Analysis of the various gravimetric soil water content (G) values is shown in Table S3. Intensity of transmitted beam (I).

The author's contributions include: Formal analysis: L.F.P. and F.A.M.C.; investigation: L.F.P. and F.A.M.C.; conceptualization: L.F.P. and F.A.M.C.; methodology: L.F.P. and F.A.M.C.; original draft preparation: L.F.P. and F.A.M.C. Each author approved the manuscript after reading the published version. All authors have approved the manuscript after reading the published version. support: This work was conducted without any outside assistance. Data Availability Statement: All data are available upon reasonable request to lfpires@uepg.br. The authors are not aware of any conflicts of interest.

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