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INVESTIGATION OF AMENDED SANDY SOIL'S WATER RETENTION CHARACTERISTICS

Amewode, E.K.[1], Sefa-Ntiri, B.[2], Owusu, A.[3], Vowotor, M.K.[4], Sackey, S.S[5], Kumi, F.[6], and Amuah, C. L. Y.[7]
[1,2,3,4,5, 7] *Department of Physics, University of Cape Coast, Ghana*
[2,5,7] *Laser and Fibre Optics Centre, Department of Physics, University of Cape Coast, Ghana*
[6] *Department of Agricultural Engineering, University of Cape Coast, Ghana*
[5]*ssackey@ucc.edu.gh*

ABSTRACT

Purpose: Soil water retention studies are important for evaluating soil quality and water movement in soils. This study assesses the water content capacity and changes in the retention curve of sandy soil after using zeolite X, activated charcoal, and rice husk ash as amendments.
Design/Methodology/Approach: Sandy soil samples were collected from the study area, Keta District of Ghana, and a core borer and a pot experiment were used to determine the pressure head and water content of the soil. One-way analysis of variance (One-way ANOVA**)** was used to analyze the data. Water retention curve analyses were conducted using COMSOL multi-physics simulation and experimental work.
Findings: The study has established that using zeolite X, activated charcoal, and rice husk ash in sandy soil amendments enhanced the water retention capability of the sandy soil provided substantial amounts and the appropriate particle size of the amendments are applied.
Research Limitation/Implication: The amendments used were restricted to zeolite X, activated charcoal, and rice husk ash.
Practical Implications: The study contributes to the field of sustainable agriculture and land management by exploring amendments that can potentially reduce water usage in irrigation, mitigate soil erosion, and enhance soil fertility. This aligns with global efforts to promote sustainable and efficient resource use.
Social Implications: These findings can be implemented for cases of poor yield by farming communities by applying zeolite X, activated charcoal, and rice husk ash to improve crop productivity.
Originality/ Value: The novelty of this study lies in the systematic usage of zeolite X, activated charcoal, and rice husk ash as amendments to modify the water content capacity and water retention content of sandy soil. It is by addressing a pressing issue in agriculture and soil science, that the study contributes valuable insights to enhance soil fertility, water management, and sustainable land use practices.

Keywords*: Activated charcoal. COMSOL. retention. simulation. water*

1. INTRODUCTION

Sandy soils are normally found to have low retention capacity for water and nutrients, have very little or no organic matter, very low acidic pH, and a high bulk density which many crops find difficult to survive in. These properties therefore render them unsuitable for farming when no soil amendments are applied (Asomaning et al., 2015; Ibrahim et al., 2016). Soil amendments lessen soil bulk density

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while increasing water retention and nutrient-retention capacity, thereby making crop production more suitable (Herath et al., 2013).

Sandy soils in Keta, Ghana, are infertile in nature, poor in plant nutrients, and have low water retention capacity. This then calls for an amendment. Zeolites are hydrated aluminosilicates containing oxides of silicon, aluminum, oxygen and counter-cations. They are soluble and consist of group I and group II earth metals that have an infinite 3D type of crystal structure. Zeolite can be both synthetic and natural respectively, and is considered to improve soil-water retention, which increases plant yield (Gholizadeh-Sarabi & Sepaskhah, 2013; Jha & Singh, 2016; Bernardi et al., 2013). Researchers have reported that applying zeolite to dry soil leads to an improvement in retention of water and nutrient, a reduction in soil bulk density and rise in porosity (Colombani et al., 2014; Enamorado-Horrutiner et al., 2016; Ibrahim-Saeedi & Sepaskhah, 2013; Bernardi et al., 2013; Colombani et al., 2014; Jha & Singh, 2016; Ghazavi. 2015). It is found that biochar which is made up of black-carbon is the result of solid remains produced by the processes such as thermal pyrolysis of manure, the residue of crops, and wastes from urban and forests under conditions of limited oxygen (Ghorbani, et al., 2022). Biochar, which includes activated charcoal and rice husk ash, is highly porous. Mixing it with soil is consequently considered a technique to improve the water retention, bulk density, porosity, and crop production capability of soil (Ghorbani et al., 2022).

Further research proved that water retention curves (WRC), which can be determined using indirect and direct methods in the laboratory, are affluent, laborious, and hard, to implement. A relatively cheaper and expedient technique is therefore required. Previous studies (Ghanba rian-Alarijeh et al., 2010) have established that WRC is important in the numerical modelling of water flow of through different soils. Software used for the simulation of the water retention curve of soils includes HYDRUS-2D and the Retention curve (RETC) (Simunek et al., 2012). In the laboratory, water retention curves are commonly estimated using pressure extractor and mid-infrared diffuse reflectance spectroscopy (Baumann et al., 2022). Alternatively, a tensiometer is used for estimating soil water retention (Kanzari et al., 2014, 2017).

A previous study has established that the nutrient and water preservation competence of sandy soil could be improved by introducing inorganic amendments, consequently improving soil potency, and physical, and hydraulic characteristics (Panda et al., 2012). Another research (Wang et al., 2016a) corroborated that modifying soil physical properties is an approach which could impact water retention in the soil, chiefly in coarse-textured soils. Using zeolite and biochar modifications to sandy soils is an innovative method to improve soil physical and chemical properties, water withholding, and hydraulic conductivity capabilities (Sarkar & Naidu, 2015).

2. METHODOLOGY

2.1 Study Area

The study area is located within latitudes 5° 471 and 5° 551 N and longitudes 0° 531 and 1° 01 E, situated in the Keta District of Ghana. It is between the Keta Lagoon, which is to its north, and the Gulf of Guinea, on its south. This is indicated in Figure 1.

The climate of that locality is that which exists in the dry tropical district, with a normal temperature of 28°C and an elevation roughly 10 m above the ocean level (Asomaning et al., 2008). There exist two rainfall peak seasons in June and September, a mean yearly rainfall of less than 900 mm and humidity ranging between 60% and 75% in the dry and rainy periods respectively. The Keta area under study was chosen as the representative of the sample study area because a USDA analysis confirmed that soil samples from that area are purely sandy (Asomaning et al., 2018). Thus, soils in the region are regularly sandy soil which is normally infertile, with irrigation and manuring forming a huge aspect of the horticultural framework in the area (Asomaning et al., 2018).

Figure 1: Map of the area under study, in the Keta District of Ghana

2.1.1 Soil collection

At the Keta study area, the sandy soil samples were collected from a land parcel, using a GPS navigator. A soil particle size distribution was analyzed at the Council for Scientific and Industrial Research, CSIR, Accra, Ghana, and the findings are presented in Table 1.

Table 1: Particle size distribution (PSD) of soil collected from Keta

Soil	Silt (%)	Sand (%)	Clay (%)	Texture (USDA)
PSD Values	0.94	98.49	0.57	Sand

2.2 Measurements and Procedure

Two techniques are used in the study to determine the retention of water by sandy soil after amendments and the results are compared. The methods are the simulation method and experimental (laboratory) method.

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2.3 Measurements: Simulation method and procedure

The simulation process used COMSOL Multiphysics 5.0 of the Earth Science Module (free version) which uses numerical methods to solve Partial Differential Equations (PDEs). A hypothetical homogeneous soil column with 2D dimensions of 0.15 m by 0.19 m was drawn during the simulation procedure. During the process, a significant assumption was made such that the Richards Equation only applies to water as the soil is at atmospheric pressure, and the air phase only has a little impact on the water movement (Šimůnek et al., 2012). Thus, the partial differential equation characterizes Richards equation as the model's governing equation. (1):

$$(C + S_e S)\frac{\partial H_p}{\partial t} + \nabla \cdot \left(-K\nabla\left(H_p + D\right)\right) = 0 \qquad (1)$$

in which H_p denotes the pressure head (m), C, represents specific water capacity (m^{-1}), Se, represents the effective saturation, S is a storage coefficient (m^{-1}), t is the time (s), K is the hydraulic conductivity ($m\ s^{-1}$), D is the direction (vertical) (m), and θ is water content (constitutive connection).

$(C + S_e S)$, the first term on the left-hand side of equation (1) describes the rate of change of storage of water content in the soil sample, while the second term $\left(-K\nabla\left(H_p + D\right)\right)$ represents the diffusion transport of water as a result of its capillarity. The specific water capacity, C, describes the change in the water content in the soil with the pressure head and is given as: e

$$\frac{\partial \theta}{\partial H_p} \qquad (2)$$

C also describes storage changes as a result of changing water content in the Richards governing equation, because: $\frac{C\partial\theta}{\partial_t} = \frac{\partial\theta}{\partial t}$ (3)

Under saturated conditions, C goes to zero at saturation, which implies that the time change in storage relates to the compression of water.

The storage coefficient (S) which is also found in equation (1) is calculated using equation (4) below:

$$S = \frac{\theta_s - \theta_r}{1[m]\cdot\rho g} \qquad (4)$$

where θ_s and θ_r denote the saturated water content and residual water content, respectively, ρ is the density of water and g is the acceleration due to gravity. The soil column was modelled as a homogenous two-dimensional medum and its water retention curve θ (Hp) was represented by the van Genucheten model given in equation (5) as: $\theta H_p) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{\left[1+|\alpha H_\rho|^n\right]^m} & H_p < 0 \\ \theta_s & H_p \geq 0 \end{cases}$ (5)

where θ is the water content, θs is the water content at saturation, θ_r, is the water content residual, and m = (1-1/n), where n is the soil pore size distribution index, assuming n > 1. Other defined parameters are α, the inverse of air entry value, and *l*, pore-connectivity of sandy soil, expected to be

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0.5. In this study, the pressure head is zero ($H_p = 0$) when the soil is deemed saturated and the pressure head is below zero ($H_p < 0$) when the soil is unsaturated.

2.3.1 Model Type, Geometry and Boundary Conditions

Due to the computer memory and simulation run times, a 2D geometry was used in the simulation. In doing so, a rectangular column with a depth of 0.15 meters and a width of 0.19 meters served as the geometry's defining feature as shown in Figure 2. During the simulation procedures, initial and boundary conditions were provided for the 2D soil model geometry (Figure 2). To simulate water flows, the top surface of the soil was given an influx boundary, the left, and right wall boundaries were given no flux conditions, and the bottom base wall was given a no-flow condition. A time step of 1 second was used during the simulations, which lasted 300 minutes.

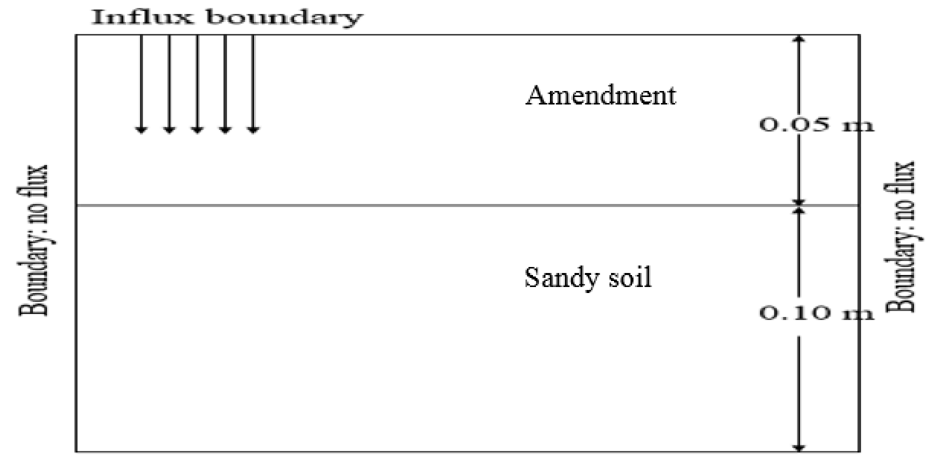

Figure 2: 2D geometry of soil column model

2.4 Laboratory Experiment

2.4.1 Amendment production

The zeolite X used in this study was purchased, while coconut shells were thermally pyrolyzed for two hours at 500 °C to produce the activated charcoal. The rice husk ash, was produced by sun-drying and burning in a furnace at 550°C for two and a half hours. Images of the produced amendments are shown in Figure 3. The rice husk ash had particle size < 1 mm, while zeolite X and activated charcoal had particle size < 2 mm.

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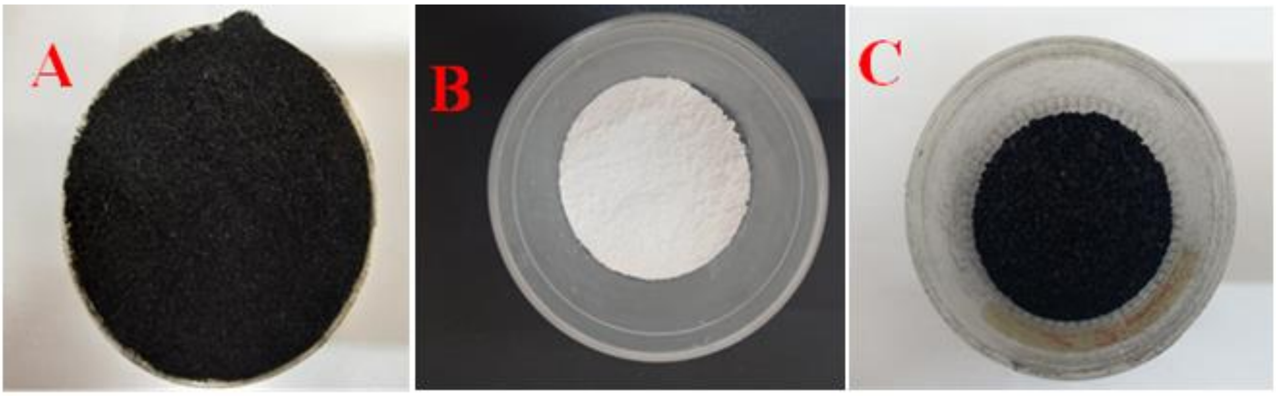

Figure 3: Pictures of amendments used:(A) Rice husk ash, (B) Zeolite X,(C) Activated charcoal

Their morphological structures were studied using microscopes, while the chemical bonds and functional groups present were established using an FTIR spectrometer.

2.5 Experimental method

A Blumat digital tensiometer was used to measure the water retention characteristics curve during the experimental stage. First of all, a soil sample from Keta was placed in the 15cm tall and 19cm diameter clear plastic containers. At the top of the soil sample, 21.0 g each of amendments namely; zeolite X, activated charcoal, and rice husk ash, was included in a band as presented in Figures 4a and 4b. Then, the tensiometer was inserted into the centre of the soil sample. Further, the soil's top surface was soaked with distilled water, and allowed to evaporate. The average was calculated after two replications. Then, 15.0 g of each of the amendments was used to repeat the process. A digital chemical balance was used to determine the water content (θ) gravimetrically, and a tensiometer was used to measure the pressure head. Measurements were carried out day-to-day for 36 days and the data collected was analyzed graphically as a graph of pressure head (H_p) against water content (θ), as presented in Figure 6.

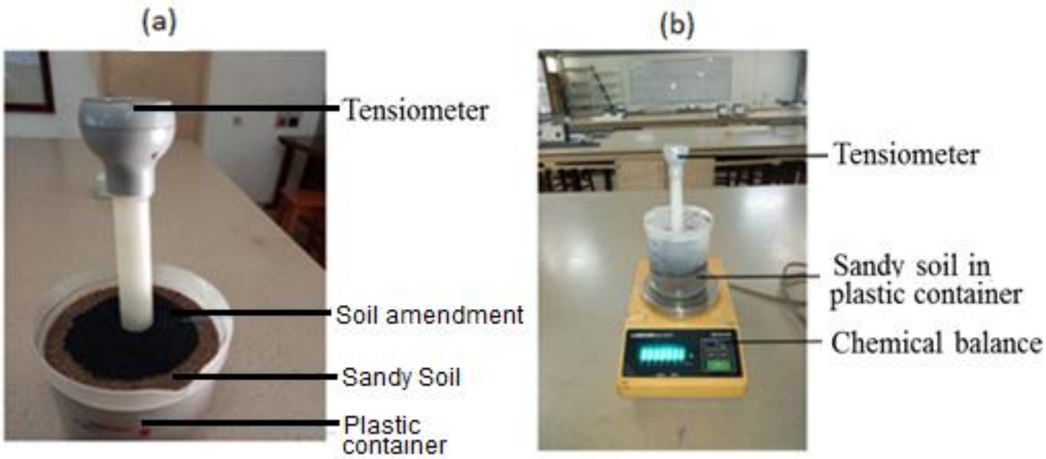

Figure 4: Photographic images of the laboratory experimental unit showing (a) soil amendment application (band method) and (b) soil water content measurement

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2.6 Soil Analysis

A 20:40 (soil: distilled water) solution portion was prepared for the determination of pH. By Jabro et al., (2020), the bulk density of the soil was determined by the cylinder technique, and the soil pH was established using a pH indicator.

2.7 Data Analysis

One-way Analysis of Variance (One-ANOVA) and Tukey's mean comparison test with a 95% confidence level were employed in statistical analysis to compare the average difference between the different soil amendments on the soil water content, as shown in Table 3. Graphs were plotted in MATLAB using the data obtained.

3. RESULTS AND DISCUSSION

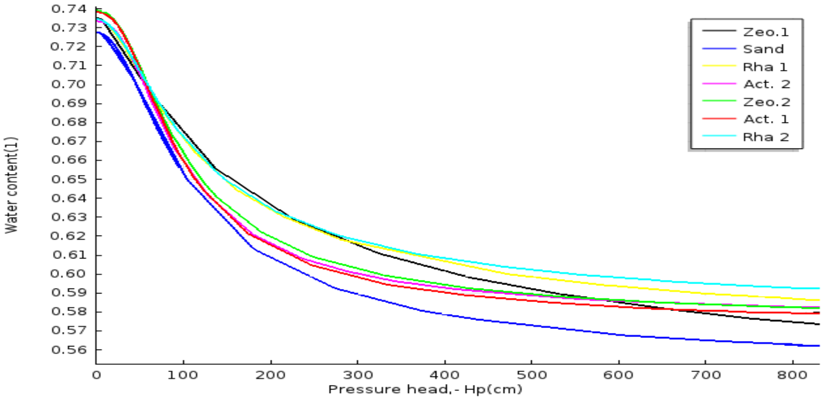

Figure 5: Water retention curve of zeolite X, rice husk ash, and activatedcharcoal amendments on sandy soil (simulation)

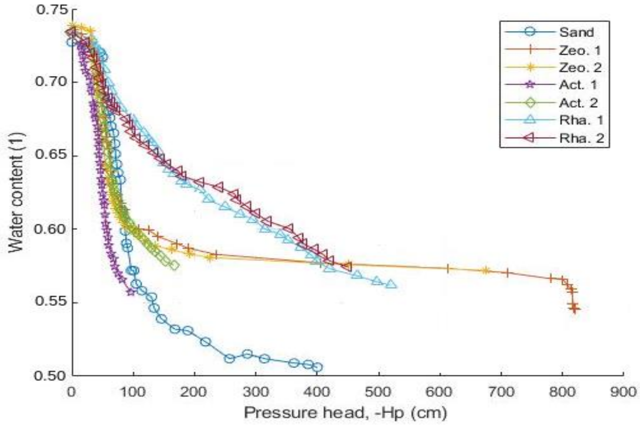

Figure 6: Water retention curve of zeolite X, rice husk ash, and activated charcoal amendments on sandy soil (experiment).

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Figures 5 and 6 show, respectively, water retention curves of the pure (unamended) sandy soil and modified sandy soil with zeolite X, activated charcoal, and rice husk ash obtained by simulation and experimental methods. Figure 5 demonstrates that with zeolite X, activated charcoal, and rice husk ash amendments, sandy soil contained less water at all pressure heads. The saturated water content (θs), varies from 0.727 for the control (pure sandy soil) to 0.734 and 0.739 for zeolites 1 and 2, 0.734 and 0.739 for rice husk ash 1 and 2, and 0.7314 and 0.7332 for activated charcoal 1 and 2, respectively, at a low-pressure head of 0 cm. It can also be deduced in Figure 5 that compared with the unamended soil (pure sandy soil), the rice husk ash (Rha) 1 and 2 preserved a little more water followed by zeolite X (Zeo) 1 and 2, and then activated charcoal (Act) 1 & 2 at all pressure heads. In Figure 6, the pressure head values for zeolite X:1 and 2 are higher compared with those of the unamended soils (pure sandy soil). This difference is attributed to the finer pore sizes of the zeolite, and also the water-retaining properties within the amended soil as the pressure head values rose ($H_p < 0$), and the soil became unsaturated. This change is attributed to the fact that the soil bulk density is decreased by zeolite and consequently improves the porosity, which improves the retention of water as reported in previous studies (Szerment et al., 2014; Sangeetha & Baskar, 2016). Results in Table 2 indicate that amending the sandy soil affects its bulk density and pH.

Table 2: Mean values of bulk density, porosity, and pH before and after sandy soil amendments

Soil	Bulk density(g/cm^3)	Porosity (%)	pH
Sandy	1.53	48.0	7.2
Zeolite 1+ sandy	1.31	50.0	7.4
Zeolite 2+ sandy	1.32	50.0	7.6
Activated charcoal 1 +sandy	1.36	49.0	7.3
Activated charcoal 2 +sandy	1.36	49.0	7.3
Rice husk ash 1 +sandy	1.34	49.0	7.4
Rice husk ash 2 +sandy	1.35	49.0	7.5

* 1 and 2 indicate masses 21.0 g and 15.0 g, respectively.

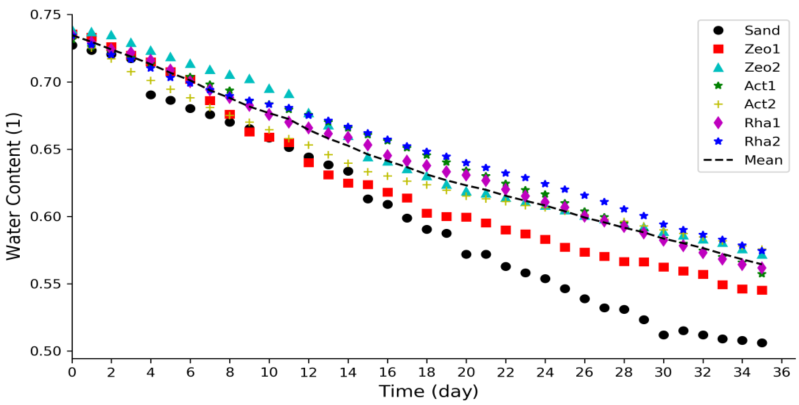

Figure 7: Variation in water content for sandy soil and soil amended at varying zeolite, activated charcoal, and rice husk ash-treated rates

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After amending the pure sandy soil with zeolite 1 and 2 as shown in Table 2, the bulk density of the testing soil reduced from 1.52 g cm^{-3} to 1.31 g cm^{-3}, respectively, while an increase was recorded in porosity. The pH of the soil increased also from 7.2 for the pure sandy soil to 7.4 and 7.6, correspondingly, with the addition of zeolite X, which agreed with previous studies (Ghorbani, et al., 2022). It was further confirmed that the effect of the addition of zeolite X on water retention can be attributed to its molecular characteristics and the capillary pressure head it utilizes which makes zeolite performance as best excellent amendment for non-wetting sands, which agrees with previous studies (Guaya et al., 2020)

In Figure 5, it is found that the zeolite X-amended sandy soil drained water more gradually and also retained a greater amount of water compared to sandy soil amended with activated charcoal. This is a result of the zeolite X retaining more water, due to the high porosity of the zeolite crystal, and also zeolites acting as a lasting reservoir of water (Sangeetha & Baskar, 2016; Bernardi et al., 2013). Research has shown that the decrease in bulk density of soil is due to the amendment of the soil using zeolite, which results in an increase in the retention capacity of water, hence, improved air movement and growth of crop roots in the soil (Mukherjee & LaI, 2013; Herath et al., 2013).

Furthermore, results in Figure 6 show an improvement in the retention capacity of water for rice husk ash 1 and 2 in all values of the pressure head compared to the soil without amendment (Pure sandy soil). These changes are because rice husk ash reduces the bulk density and improves the porosity, which therefore improves the retention of water as established in a study (Zheyong et al., 2023; Abel et al., 2013). Table 2 confirms that the modification of the bulk density of soil and the pH of sandy soil is due to the addition of rice husk ash to the soil. It is shown that the applications of rice husk ash to the pure sandy soil saw an improvement in soil porosity and a decrease in bulk density when compared with the control soil (pure sandy soil) as presented in Table 2. From Table 2, amending pure sandy soil with zeolite X increases the pH of the sandy soil from 7.2 to 7.4 (7.6), respectively, which agrees with a previous study (Rogovska et al., 2014). The findings show that sandy soil water retention is dependent on the amendment used, vis-à-vis rice husk ash, it is in agreement with the recent research of Zheyong et al. (2023). From Figure 7, it is found that the rice husk ash-amended sandy soil drained water more gradually and also retained water more than sandy soil amended with activated charcoal. Research shows that a reduction in bulk density of soil is a result of amending the soil using rice husk ash; resulting in an improvement in the holding capacity of water, hence, improved air movement and growth of crop roots in the soil. (Mukherjee & LaI, 2013; Herath et al., 2013). The variations in water retention improvement might be a result of the soil pore size distribution, larger surface area, and its ability to absorb water.

Activated charcoal 1 and 2 had the same effect on the unamended soil (pure sand) concerning its water retention ability. From Table 2, the bulk density of pure sandy soil reduces from 1.53 g cm^{-3} to 1.36 g cm^{-3} for both activated charcoal 1 and 2 applications, indicating an increase in soil porosity, and the pH content also increasing from 7.2 for the sandy soil to 7.3 for both 1 & 2 applications. This is in agreement with a previous study (Ghorbani et al., 2022).

In all, the results obtained indicate that soil water retention capacity is heavily influenced by the addition of zeolite X, activated charcoal, and rice husk ash, as shown in Figure 6, which agrees with other researchers (Ghorbani et al., 2022; Abel et al., 2013). It is further observed that at all values of

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pressure heads the rice husk ash and zeolite X amendments improved the water-holding capacity. The variances between the water-holding curves for the amended soils were observed not only for low-pressure head values but also for high-pressure head values. Water retention capacity at a higher-pressure head primarily depends on capillarity and pore size distribution, while water retention capacity at a lower pressure head is a result of its surface adsorption. From Figure 6, the best amendment was zeolite X which increased the amount of water in the sandy soil, then the rice husk ash, and finally, the activated charcoal compared to the unamended soil. The improvement in water retention due to the addition of zeolite, activated charcoal, and rice husk ash is attributed to the macro and micropores of the amendments which increase the porosity and reduce the bulk density (Ghorbani, et al., 2022). The water retention curve obtained using simulation (Figure 5) agrees well with the laboratory results (Figure 6), though with marginal differences at the pressure heads. This agrees with other studies (Baronti et al., 2014; Herath et al., 2013; Abel et al., 2013).

Figure 7 shows the effect of soil amendments on water content with time (days). The soil-amended water content improved compared to the pure sandy soil, although they all exhibited a reducing pattern over the period. The graph also indicates a rise in the water retention capability of the soil treated with zeolite X, rice husk ash, and activated charcoal to better retain water when evaluated against the control soil. Comparable findings have been documented in other research (Herath et al., 2013; Bernardi et al., 2013).

The one-way ANOVA conducted showed significant differences among the treatment means ($p = 0.006$) and as a result, a follow-up Tukey comparison test was done as presented in Table 3.

Table 3: Descriptive statistics performance of various soil amendments on water content of the sandy soil using Tukey 95% simultaneous confidence interval

Difference of Level	Difference of Means	95% confidence intervals
Zeo1 – Sand	0.02020	(-0.01959, 0.05986)
Zeo2 – Sand	0.04429	(0.00455, 0.08399)
Act1 – Sand	0.04292	(0.00318, 0.08262)
Act2 – Sand	0.03323	(-0.00651, 0.07294)
Rha1 – Sand	0.03951	(-0.00023, 0.07922)
Rha2 – Sand	0.04740	(0.00766, 0.08711)

This means significant differences in water content among various soil amendments application at $p < 0.05$

In Table 3, the Tukey 95% confidence interval used was to prove whether the confidence interval contains the true differences in the treatments. It can be deduced that the pairs which contain zero in their confidence intervals are the same. Though the means of zeolite 1 and activated charcoal 2 recorded higher means in water content than sand, Tukey's simultaneous test established that the variation is not statistically substantial. Also, since the 95% confidence interval of zeolite 2 and sand (0.00455, 0.08399), activated charcoal 1 and sand (0.00318, 0.08262), and rice husk ash 2 and sand (0.00766, 0.08711) did not contain zero, it suggests an important difference between each of the pairs. This can be attributed to the temperature at which the amendments were produced, the feedstock used, the amount of dosage applied, and the particle sizes of the amendments used.

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4. CONCLUSION

The study has established that zeolite X, activated charcoal, and rice husk ash applications to sandy soil will enhance the water retention capability of sandy soil provided substantial amounts and the appropriate particle size of the amendments are applied. Simulation using the COMSOL Multiphysics technique has also proved to be appropriate in estimating the water retention changes in sandy soil. The results suggest the advantages of amended sandy soil concerning improvements in its water retention capacity, and therefore, an effective way of boosting the soil's capability to retain moisture and store nutrients. The study also examines how these amendments modify the properties of sandy soil. This includes changes in water retention, porosity, bulk density, and pH levels. Such comprehensive analysis provides insights into the multifaceted impacts of amendments on soils. The study's inclusion of multiple amendments (zeolite X, activated charcoal, and rice husk ash) offers a comparative analysis of their effectiveness. This comparative approach helps identify the most suitable amendment(s) for specific soil improvement goals.

These findings can be implemented for cases of poor yield by the farming community in Keta, and indeed, any part of the world, by applying zeolite X, activated charcoal, and rice husk ash to improve crop productivity. The adoption of soil improvement practices, as recommended by the study, can create opportunities for local businesses involved in the production and distribution of soil amendments. This can stimulate economic growth and employment in rural areas. Sandy soils are susceptible to erosion, which can have detrimental effects on land quality and nearby water bodies. Improved soil structure resulting from amendments can reduce soil erosion, preserve fertile land and prevent sedimentation in rivers and lakes.

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