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Research Article

Determination of Evapotranspiration and Crop Coefficients of Irrigated Legumes on Different Soil Textures Using the FAO56 Approach

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Climate- and location-specific crop coefficients (K_c) play pivotal roles in effective water management and crop yield optimization. Research on K_c for many staple crops remains limited in many regions across Africa. This study examined the crop coefficients of two varieties of cowpea (Sampea 14 and Sampea 17) and a variety of soybean (TGX 1465-1D) across different soil textures for optimized water management and crop yield. This study ascertained the K_c of Sampea14 (V1), Sampea17 (V2), and TGX 1465-1D (V3) cultivated on sandy, sandy clay loam, and sandy loam soils within Port Harcourt, Southern Nigeria. This formed a 3 by 3 factorial experiment in three replicates. Changes in soil water content and crops' agronomic parameters were monitored regularly. Meteorological data were obtained from the National Aeronautic and Space Administration website, and reference evapotranspiration was estimated from the meteorological data using the FAO Penman Monteith method. K_c were estimated from the actual crop water use and reference crop evapotranspiration using the FAO56 method. During the initial growth stage, the average K_c for V1, V2, and V3 were computed as 0.55, 0.72, and 0.81, respectively. At the mid-growth stage, these coefficients increased to 1.48, 1.30, and 1.60, and at the late season, the average K_c were 0.80, 0.69, and 0.86 for the respective varieties. The findings from this study hold the potential to significantly contribute to proper water management practices in the studied area. The understanding of K_c for these specific legume varieties across different soil textures offers valuable insights for optimizing irrigation scheduling and ultimately enhancing crop yield and water productivity.

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1. Introduction

Legumes are cost-effective nutrient sources and potential income generators for subsistence farmers lacking access to costly irrigation and fertilizers. Legumes serve as cover crops to mitigate soil erosion and demonstrate remarkable resilience to both water stress and waterlogging throughout their growth cycle[1]. Furthermore, their symbiotic relationship with nitrogen-fixing Rhizopus in root nodules renders them valuable in crop rotation[2]. According to the National Agricultural Extension Research Services (NAERLS)[3] and the National Programme on Agriculture and Food Security (NPAFS)[4], the total production of cowpea and soybean was 1,561,964 and 491,504 t/ha, respectively, between 2007 and 2011. This implies that one of the foci of the Nigerian nation in the agricultural sector is to engage in intensified legume production with optimal inputs and management.

Evapotranspiration is the total water loss from plants due to transpiration and soil surface evaporation, influenced by factors such as temperature, humidity, sunlight, wind, and vegetation cover[5]. Water regularly evaporates from various surfaces, including lakes, rivers, pavements, soils, and wet vegetation[6]. Different crops also have distinct water requirements or transpiration requirements at different growth stages, primarily determined by crop coefficients (K_c), which play a crucial role in estimating crop water needs[7][8]. Crop coefficients are inherent crop characteristics used to calculate crop evapotranspiration or water requirements (ET_c)[9]. They compare the evapotranspiration of the specific crop to a well-calibrated reference crop under identical conditions. Crop Water Requirement (CWR) (mm) measures the evapotranspiration when soil water is adequate due to precipitation or irrigation, supporting unhindered plant growth and yield[10]. It also ensures water remains within the root system's absorption capacity[11]. According to Sultana et al.[12], CWR represents the water depth required to fulfil ET_c by a disease-free crop under unrestricted soil conditions, including water and fertility, to achieve maximum production potential in the given environment. Factors such as daily temperature, relative humidity, and wind velocity influence the CWR[13]. Consequently, crops in hot, dry, windy, and sunny climates typically have the highest water requirements[10].

The crop coefficient (K_c) is typically determined through empirical experimentation and encompasses the cumulative impact of multiple factors such as changes in leaf area, plant height, crop attributes, irrigation methods, developmental rate, planting date, canopy cover, canopy resistance, soil and climatic conditions, and agricultural management practices[14]. Each crop is associated with a specific set of K_c values, which project varying water utilization across different crops during distinct growth stages[15]. The duration of these stages is contingent on local climate, latitude, elevation, planting date, crop type, and agricultural techniques. The most precise determination of a crop's growth stage, and subsequent adjustment of empirical K_c values, is achieved through on-site observations[16]. According to Pereira et al.[15], during the initial stages of crop germination and establishment, the majority of evapotranspiration (ET_c) primarily comprises soil surface evaporation, resulting in lower crop water use rates and smaller K_c values (referred to as the $K_{c\ \text{initial stage}}$). As the crop matures, with its canopy expanding to cover the soil surface, soil surface evaporation diminishes, and the transpiration component of ET rises. Agronomical plants reach their maximum ET_c rate when fully developed (referred to as the $K_{c\ mid-season}$), but as the season nears its end and the plant reaches physiological maturity, the ET rate decreases (referred to as the $K_{c\ end\ season}$)[15].

According to Wang et al.[17] and Fan et al.[18], crop water consumption is a crucial factor in assessing the viability of crop cultivation in any given region. In recent times, crop coefficients of various crops have been investigated using various methods. For instance, Hassan et al.[19] utilized remote sensing and meteorological data to monitor plant phenology and estimate crop coefficients and evapotranspiration. They reported a strong coefficient of determination (0.98) between field crop coefficients derived from meteorological data and those predicted from an NDVI value of 0.147. In another study, Dingre et al. [20] investigated the relationship between field water balance-derived crop coefficients and canopy reflectance-based NDVI for irrigated sugarcane. This relationship was described by a second-order polynomial regression equation. Similarly, Puig-Sirera et al. determined the transpiration and water use of a traditional olive grove under irrigation using the sap flow method and the FAO56 dual crop coefficient approach. Their findings indicated that the basal crop coefficient (K_{cb}) for the mid-season of the olive grove ranged from 0.40 to 0.45, while at the end of the season, K_{cb} ranged between 0.35 and 0.40.

In the context of Tangara da Serra, MT, Brazil, Bariviera et al.[21] determined the dual crop coefficient for an early cycle soybean cultivar using a precise lysimeter. They reported K_{cb} and soil evaporation (K_e) values of 0.47, 1.15, 0.89 and 0.94, 0.14, 0.44 for the early, mid, and late growth stages, respectively. Additionally, Gong et al.[22] conducted research on tomato cultivation in a solar greenhouse under both full and deficit irrigation conditions. They observed maximum crop evapotranspiration ranging from 0.15 to 1.88 mm/h under full irrigation and 0.15 to 0.89 mm/h under deficit irrigation. The average daily standard evapotranspiration was 5.11 mm/day, with a seasonal evapotranspiration of 1814 mm. The crop coefficients for citrus trees in the study by Jamshidi et al. [23] ranged from 0.67 to 0.96. Lastly, in the semi-arid climate of the Senegal River Valley, average crop coefficient values of 1.01, 1.31, and 1.12 were reported for rice during the crop development, mid-season, and late-season growth stages[24].

In many regions across Africa, comprehensive research on crop coefficients for key staple crops remains limited due to the diverse climatic variations[1]. This study was thus designed to examine the crop coefficients of specific legumes across different soil textures for optimized water management and crop yield. The primary objective of this study is to determine the crop coefficients (K_c) of three distinct legume species—Sampea 14 (V1), Sampea 17 (V2) of cowpea, and TGX 1465-1D (V3) of soybean. The FAO56 approach was employed to determine the K_c values from the directly measured actual crop water use and estimated reference evapotranspiration. According to Cardova et al.[25], the FAO56 method is of great benefit because it provides structures for standardizing potential evapotranspiration. This research is conducted across various soil textures, including sandy, sandy clay loam, and sandy loam soils. The investigation spans multiple growth stages, encompassing emergence (initial), flowering (development), pod-setting (mid), and maturity (late), all within the prevailing climatic conditions of Port Harcourt, located in southern Nigeria. Results from this study would enable irrigation planning and water management in the cultivation of different varieties of soybean and cowpea on different soil textures.

2. Materials and Methods

2.1. Study Area

This study was conducted at the agricultural research station within the Department of Crop and Soil Science, situated in the Faculty of Agriculture at the University of Port Harcourt. This facility is located at coordinates 4.847°N latitude and 6.975°E longitude, as illustrated in Figure 1. It is positioned in the Obio/Akpor Local Government Area of Rivers State, Nigeria, at an elevation of approximately 15.85 meters above mean sea level. The climate in Port Harcourt is predominantly humid, characterized by an average annual precipitation of 2,293 mm, and the mean annual temperature and relative humidity levels are approximately 28°C and 75%, respectively.

2.2. Experimental Design

The study was designed as a 3 x 3 factorial experiment, with three replications within a controlled environment. Twenty-seven experimental plots (each with a 4 m^2 size) were used for the experiment while considering an effective root zone depth of 0.5 m. The experimental treatments consisted of three different varieties of leguminous crops, namely two cowpea types (Sampea 14 and Sampea 17) and one type of soybean (TGX 1465-1D). The experiment also considered three distinct soil textures, specifically sandy, sandy clay loam, and sandy loam soils. Detailed descriptions are shown in Figure 2. Some soil movements from other sites were done to ensure planting beds were made from the specified soil textures.

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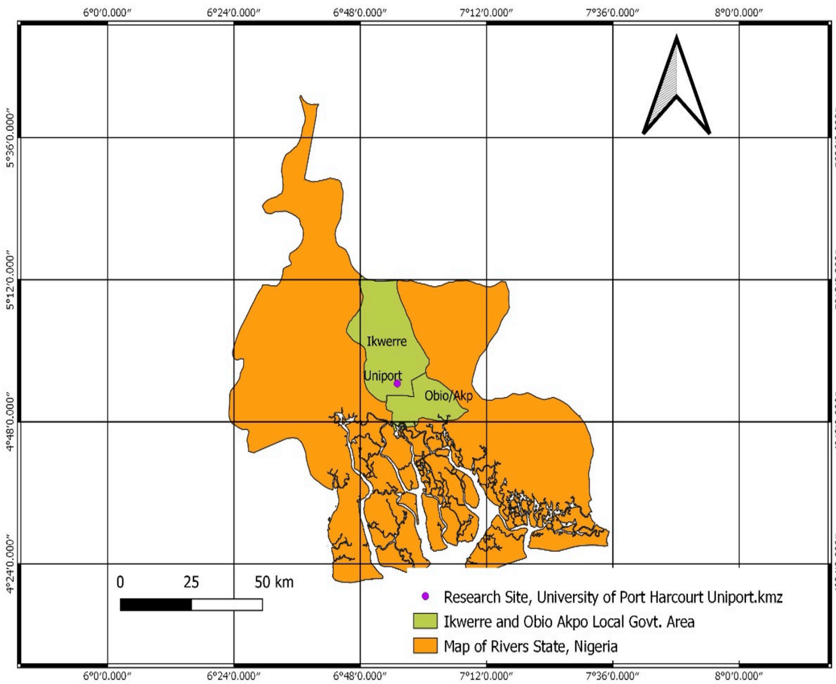

Figure 1. Map of Rivers State, Delineating Obio-Akpor Local Government, Nigeria

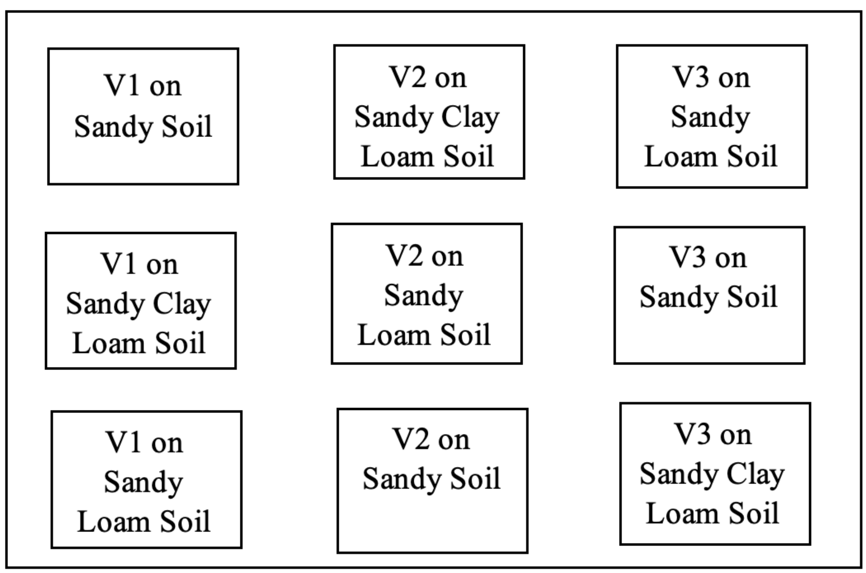

Figure 2. Detailed Description of the Experimental Set-up

2.3. Physicochemical Properties of Experimental Soils

The bulk densities of the sand, sandy clay, and sandy clay loam soils also indicated the level of compaction, which influences the soil water holding capacity, water movement, plant water availability, and crop rooting depth[26]. Investigations on bulk densities, hydraulic conductivities, and particle size analysis were carried out on collected soil samples. The saturated hydraulic conductivity was investigated using the method specified by Reynolds et al.,[27]. Soils' bulk densities were determined according to the Blake and Hartage method[28]. Soil particle size distributions were analysed to determine the relative proportion of sand, silt, and clay in the soils using the hydrometer method as described by Gavlack et al.[29].

The investigation of total nitrogen, total phosphorus, cation exchange capacity, calcium, magnesium, and potassium content was carried out on collected soil samples to determine the soil nutrient level and to inform the level of needed fertilizer application to the crops. The total nitrogen was determined according to the O'Dell[30] method. The total phosphorus was determined using the colorimetric, ascorbic acid, two reagents (1978) method. The Cation Exchange Capacity (CEC) is a measure of the number of ions that can be adsorbed in an exchangeable fashion on the negative charge sites of the soil[31]. The CEC was determined according to the Bache[31] method, which is known as the ammonium acetate extraction method. Calcium, magnesium, and potassium were determined using the calcium chloride extraction method described by Houba et al.[32].

2.4. Planting and Crop Management

Three different varieties of leguminous crops were planted on March 15, 2022. These varieties included Sampea 14 (V1), Sampea 17 (V2), and TGX 1465-1D (V3). The planting depth was 2 cm below the soil surface. Each legume variety was planted on three distinct soil textures in three replicates, resulting in a total of 27 experimental plots with nine plots per replicate. The experiment lasted for 15 weeks and concluded on July 18, 2022. The experiment's duration was divided into specific growth stages (emergence, flowering, pod setting, and maturity) as defined by Allen et al.[33]. During the experiment, water use and crop coefficients were estimated at three stages: the initial (15 days for soybeans and 20 days for cowpea varieties), mid-season (55 days for soybeans and 60 days for cowpea varieties), and late stages (15 days for soybeans and 20 days for cowpea varieties) [33].

To enhance the nutrient content of the collected soil samples, granular water-soluble fertilizers with a ratio of N: P: K at 6: 25: 5 were applied to the soil surface before planting, following the recommended agronomic rate of 50 kg/ha based on the soil chemical analysis. Fertilizer application was repeated 21 days after planting to promote the crops' healthy development. Weed control measures were implemented to maintain disease-free plants and prevent competition with the main crops for nutrients and water. Throughout the crops' growth period, efforts were made to prevent water stress. Irrigation water was consistently applied manually using a watering can whenever the soil water content reduced to 40% of the soil's field capacity. Irrigation water was applied to return the soil back to 100% field capacity.

2.5. Agrometeorological Data Collection

Daily remotely sensed agrometeorological data for the experimental location (4.847 °N, 6.975 °E) were obtained from the National Aeronautics and Space Administration's (NASA) website (https://power.larc.nasa.gov/data-access-viewer/). Data collected include daily minimum and maximum temperature, daily maximum and minimum relative humidity, daily average wind velocity, and mean hours of daily sunlight. Collected data spanned from the 1st of March 1981 to the 31st of July 2022. These data were employed for the estimation of reference evapotranspiration throughout the growth period of the planted crops.

2.6. Estimation of Reference Evapotranspiration (ET_p)

Among all methods, the Penman-Monteith equation has been recommended by the Food and Agriculture Organisation (FAO) as the standard method for the computation of ET_p, especially under arid conditions[33]. Adesogan and Sasanya[34] also recommended the method, since the Reference Evapotranspiration (ET_p) values obtained from it were closely related to measured ET_p values from a class A evaporation pan.

The reference evapotranspiration (ET_p) at the growth stages of the crops was thus computed for the growing period by the Penman-Monteith Method. The FAO-56 recommended method was chosen for its accuracy in the estimation of ET_p from climatological data[34]. Daily ET_p was estimated from Equations 1 to 11.

$$PET = \frac{0.408\Delta\left(R_n - G\right) + \gamma\frac{900}{T+273}U_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)} \tag{1}$$

$$R_s = \left(a_s + b_s\frac{n}{N}\right)R_a \tag{2}$$

$$R_{so} = \left(0.75 + 2\mathrm{z} * 10^{-5}\right)R_a \tag{3}$$

$$R_{ns} = (1-\alpha)R_s \tag{4}$$

$$R_{nl} = \sigma\left[\frac{\left(T_{\max k}\right)^4 + \left(T_{\min k}\right)^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \tag{5}$$

$$G = 0.14(T_{MONTH\ i} - T_{MONTH\ I-1}) \tag{6}$$

Where: R_n = Average net radiation at the crop surface (MJ/m^2/day), G is soil flux density (MJ/m^2/day), γ = Psychometric constant (kPa/ ^0C) = 0.067, U_2 = Wind velocity at 2m height (m/s), e_s = Saturation vapor pressure (kPa), e_a = Actual vapor pressure (kPa), $e_s - e_a$ = Saturation vapor pressure deficit (kPa), T = air temperature at 2m height (^0C), Δ = Slope vapor pressure curve (kPa/ ^0C).

R_s is the incoming solar radiation; obtained from the relationship between Angstrom values a_s = 0.25, b_s = 0.5, and R_a. (equation 1b). R_{so} is the clear sky solar radiation obtained from elevation (z m) and R_a (equation 1c). R_{ns} is the shortwave radiation; calculated from albedo (α) and R_s (equation 1e). R_{nl} was estimated from equation (1e). σ is the Stefan-Boltzmann constant = 4.903 x 10^{-9} MJ/ K^4/m^2/day, T_{maxk} and T_{mink} are absolute values of monthly minimum and maximum temperatures. R_n was calculated as the difference between the net long wave radiation (R_{nl}) and net shortwave radiation (R_{ns}) measured in MJ/m^2/day. The soil flux G was obtained from equation 1f. $T_{MONTH\ i}$ is the mean temperature of the present month, and $T_{MONTH\ i-1}$ is the mean temperature of the previous month in ^0C. 0.408 is a constant which converts the unit MJ/m^2/day to mm/day.

$$e_S = e^o\left(T_{\text{mean}}\right) = 0.611\exp\left(\frac{17.27T_{\text{mean}}}{T_{\text{mean}} + 237.3}\right) \tag{7}$$

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$$\Delta = \frac{4098e_s}{(T+237.3)^2} \tag{8}$$

$$e_{a_1} = \frac{e^o\left(T_{\min}\right) x RH_{\max}}{100} \tag{9}$$

$$e_{a_2} = \frac{e^o\left(T_{\max}\right) x RH_{\min}}{100} \tag{10}$$

$$e_a = \frac{e_{a_1} + e_{a_2}}{2} \tag{11}$$

Where: RH_{max} = Maximum relative humidity (%), RH_{min} = Minimum relative humidity (%). T_{min}, T_{max}, and T_{mean} are the monthly minimum, maximum, and mean temperatures in ^{0}C.

2.7. Collection of Water Use and Agronomic Data

Depletion in the soil water content and changes in the agronomic properties of the planted crops were monitored and measured on a weekly basis. These enabled the monitoring of the evapotranspiration rate and changes in plant development.

2.7.1. Monitoring Soil Moisture Depletion

The soil moisture was monitored from the water balance Equation (Equation 12). Depletion of soil moisture was monitored using the gravimetric method as employed by Alla Jabow et al.[35] and Djaman et al.[24].

$$ET_c = I + R_a + G - R - D \mp \Delta S \tag{12}$$

Where: I is Irrigation, R_a is the rainfall, G is capillary water, R is runoff, D is deep drainage, ΔS is the change in soil moisture. 'I' was considered to be equal to zero before and after irrigation as and when needed, R_a is zero during the cultivation period since the experiment was done in a controlled environment, and the groundwater table in the study area is not close to the soil surface; therefore, the capillary rise from groundwater G was zero. Runoff and deep drainage were zero since the right amount of irrigation water was applied without permitting excesses.

The change in soil moisture (ΔS) was estimated by collecting soil samples from the effective root zone, weekly, in replicates, from each experimental plot, by means of the soil core samplers. Soil samples in soil core samplers were oven-dried for 24 hours at 105°C, and the dry weight was determined afterward. These were done before and after water application. Weekly depletion of soil was determined from Equation 13.

$$\Delta S = \frac{SWC1 - SWC2}{\Delta t} \tag{13}$$

Where: ΔS is the gravimetric weekly water depletion (g/g), SWC1= Soil water content at week 1 (g/g), SWC2 = Soil water content at week 2 (g/g), Δt is the change in time.

The gravimetric water content was converted to volumetric water content using Equation 14. The volumetric water depletion is equivalent to the actual evapotranspiration (ET_c) of water used by the crops. The seasonal ET_c was estimated from the total ET_c over the cultivation period from planting to harvesting.

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$$\Delta \mathrm{d} = 1000 \times \rho \times \Delta S \tag{14}$$

Where: Δd= change in soil water depth (mm/m), ρ = dry bulk density (g/cm^3), ΔS= Change in gravimetric moisture content (g/g).

2.7.2. Crop Data Collection

Agronomic data including plant height, leaf length, leaf width, number of leaves, and leaf area index were measured weekly starting from the 7th day after planting. The leaf area index (LAI) is the green leaf area of plants per unit area. The plant height (cm), leaf length (cm), and leaf width (cm) were measured weekly using a meter rule. The LAI was estimated from Equation 15.

$$LAI = \frac{a \times LL \times LW}{CA} \tag{15}$$

Where: a is the shape factor (2.018)[36], (LL= Leaf Length, LW= Leaf Width, and CA= Cultivated Area

2.8. Estimation of Crop Coefficients from the FAO56 Approach

The crop coefficients (K_c) values represent the integrated effects of changes in leaf area, plant height, crop characteristics, irrigation method, rate of crop development, crop planting date, degree of canopy cover, canopy resistance, soil and climate conditions, and management practices[33]. Each crop will have a set of specific crop coefficients and will predict different water use for different crops at different growth stages. Crop coefficients were estimated for each growth stage from Equation 16.

$$Kc = \frac{ET_c}{ET_p} \tag{16}$$

Where: K_c= Crop Coefficient, ET_c= Actual Crop Evapotranspiration (mm/week), ET_p= Reference Evapotranspiration (mm/week)

2.9. Data analysis

Analysis of variance (ANOVA) was used to statistically determine the differences in measured means and variances of all data. The doebioresearch statistical package in R Studio 4.1.3 (released 10th March, 2022) was used for the statistical analysis. Least significant difference (LSD) was used to separate all means at the 95% level of confidence.

3. Results and Discussions

3.1. Soil Physicochemical Properties

Table 1 presents the means and standard deviations of the soils' bulk densities, hydraulic conductivities, nitrogen, phosphorus, potassium, calcium, magnesium contents, and cation exchange capacities. The bulk densities of the soil samples exhibited a range from 1.40 g/cm^3 to 1.55 g/cm^3. Notably, sandy soil displayed the highest bulk density, whereas loam and clay soils exhibited similar bulk density values. In terms of saturated hydraulic conductivities, there were no significant variations observed among the three soil textures, with values ranging from a maximum of 0.11 cm/sec to a minimum of 0.09 cm/sec, as detailed in Table 1. The

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results pertaining to saturated hydraulic conductivity indicated a close proximity between the values for sandy clay loam and sandy loam soils, particularly. Specifically, the mean bulk density of sand was found to be 1.55 g/cm^3, which was significantly higher when compared to the values obtained for both sandy clay loam (1.40 g/cm^3) and sandy loam (1.45 g/cm^3) at a significance level of $p \leq 0.05$. The percentages of sand, silt, and clay were used to separate the soil into their respective textural classes as shown in Table 1, and applied throughout the study.

The chemical properties analysed gave clues to the nutrient status of the soils. The sandy clay loam soil has the highest nitrogen and phosphorus contents as compared to the other soil textures. The sandy soil, however, has the highest potassium content, while the calcium and magnesium contents of the sandy loam soils are higher than those of the other two textures. The highest CEC was also found in the sandy clay loam. Statistically, the chemical properties inherent in the three soil textures are significantly different from one texture to another.

Physical Parameters	**Sandy**	**Sandy Clay Loam**	**Sandy Loam**	**LSD ($p < 0.05$)**
Bulk Density (g/cm^3)	1.55±0.11^a	1.40±0.12^b	1.45±/0.09^b	0.12
Hydraulic Conductivity (cm/s)	0.11±0.02^a	0.09±0.03^a	0.10±0.03^a	0.02
Sand (%)	91.11±3.56^a	74.72±2.99^c	75.83±3.12^b	2.08E-14
Clay (%)	7.22±2.99^c	23.33±3.12^a	18.06±3.07^b	3.55E-14
Silt (%)	1.67±2.87^c	1.95±1.94^b	6.11±1.71^a	6.74E-14
Nitrogen (mg/kg)	0.048±0.001^b	0.058±0.001^a	0.044±0.001^c	0.002
Phosphorus (mg/kg)	6.13±0.01^c	8.23±0.01^a	6.93±0.01^b	0.020
Potassium (mg/kg)	21.86±0.01^a	17.28±0.01^b	15.20±0.02^c	0.116
Calcium (mg/kg)	1.12±0.01^b	0.50±0.01^c	1.26±0.01^a	0.020
Magnesium (mg/kg)	0.08±0.01^c	0.14±0.01^b	0.20±0.01^a	0.020
CEC (cmol/kg)	7.82±0.00^b	13.69±0.00^a	7.37±0.00^c	0.020

Table 1. Mean and Standard Deviation of Soils' Physicochemical Properties for Different Soil Textural Class

**Values with the same superscripts are not significantly different. LSD is Least Significant Difference*

3.2. Agronomic Growth Parameters

3.2.1. Plant Height

Table 2 provides an overview of the mean plant heights and their standard deviations recorded throughout the growth stages of three different legume

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varieties. During the emergence stage after planting, the plant heights ranged from 18.83 cm to 36.17 cm across the various legume varieties grown on the three soil textures. When flowering occurred, plant heights ranged from 31.43 cm (V3 on sandy soil) to 59.40 cm (V2 on sandy soil). Notably, V2's height differed significantly from V3's height on sandy soil during this stage.

Moving to the pod setting growth stage, a significant difference was observed between V1 on sandy soil and V2 on sandy clay loam. This trend persisted into the maturity stage. Interestingly, the performance of V2 on sandy clay loam soil exhibited the lowest plant height. The maximum plant height recorded at maturity was 115.50 cm, observed in V1 on sandy soils. Between the flowering and emergence stages, plant heights for varieties 1, 2, and 3 increased by average percentages of 40.29%, 31.24%, and 31.74%, respectively. However, between the pod setting and maturity stages, the growth rate slowed down, resulting in average increases of 17.73 cm, 16.26 cm, and 0.60 cm for Varieties 1, 2, and 3, respectively.

Notably, legume varieties planted in sandy soil exhibited the highest range of plant heights (27.50 to 115.50 cm), whereas those planted on sandy clay loam had the lowest plant height range (18.83 to 97.17 cm). This discrepancy may be attributed to root restriction due to the compacted nature of clay soil, which hinders the plants' ability to adequately absorb water from the soil[37].

Growth Stages	**Variety/Treatment**	**Sandy**	**Sandy Clay Loam**	**Sandy Loam**
Emergence	V1	27.50± 1.22^{abc}	30.00±3.77^{ab}	26.17±5.10^{bc}
	V2	36.17±4.13^{a}	30.83±1.65^{ab}	33.17±4.90^{ab}
	V3	26.50±1.63^{bc}	32.67±8.99^{ab}	18.83±4.50^{c}
	LSD ($p < 0.05$)	9.44		
Flowering	V1	56.50± 9.39^{a}	42.00±5.72^{ab}	44.33±6.51^{ab}
	V2	59.40±22.34^{a}	42.93±2.67^{ab}	45.10±5.78^{ab}
	V3	31.43±14.70^{b}	44.17±11.26^{ab}	40.50±11.50^{ab}
	LSD ($p < 0.05$)	24.49		
Pod setting	V1	97.00±2.45^{a}	73.33±15.56^{ab}	72.17±9.72^{ab}
	V2	90.83±43.41^{ab}	55.17±8.37^{b}	56.33±5.24^{ab}
	V3	75.83±24.87^{ab}	92.00±15.58^{ab}	95.50±14.84^{ab}
	LSD ($p < 0.05$)	40.68		
Maturity	V1	115.50±1.22^{a}	100.50±3.27^{ab}	80.33±13.68^{ab}
	V2	99.00±42.43^{ab}	55.67±8.18^{b}	93.33±45.73^{ab}
	V3	75.90±11.64^{ab}	92.00±11.66^{ab}	97.17±15.97^{ab}
	LSD ($p < 0.05$)	46.74		

Table 2. Mean and Standard Deviation of Plant Height of Legume Varieties at Different Growth Stages (cm)

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Values with the same superscripts are not significantly different. V1 is variety 1 of cowpea (sampea 14), V2 is variety 2 of cowpea (sampea 17), and V3 is a variety of soybean (TGX 1465-1D), LSD is Least Significant Difference

3.2.2. Number of Leaves

The number of leaves generated by the various legume varieties at specific growth stages is a crucial parameter for assessing crop transpiration and water usage. The resulting leaf numbers for the planted legume varieties are presented in Table 3. During the emergence stage, the number of leaves observed across the three soil textures ranged from 4 to 9. Notably, V1 cultivated on sandy soil exhibited the highest leaf count (9), while the same variety on sandy clay loam soil had the lowest leaf count (4). Among the legume varieties, V2 produced the highest number of leaves across all three soil textures.

As the flowering stage approached, V1 on sandy loam soil displayed the highest leaf numbers (16), whereas V1 on sandy clay loam had the lowest leaf count (6). When the legumes entered the pod-setting stage, V3 on sandy loam soil bore the highest number of true leaves (30), whereas V1 and V2 on sandy clay loam exhibited the lowest leaf numbers (10). However, at maturity, V1 on sandy soil had the highest number of true leaves (34), while V2 on sandy clay loam had the lowest leaf count (14).

Between the flowering and emergence stages, there was a substantial increase in the number of leaves for each variety, with V1, V2, and V3 showing average percentage increases of 47.36%, 40.76%, and 33.33%, respectively. However, between the pod-setting and maturity stages, the rate of increase in leaf numbers slowed down to 27.68%, 25.00%, and 8.39%, respectively. This phenomenon can be attributed to physiological leaf deterioration, aging, and leaf shedding[38].

Statistically, significant differences were observed at emergence in the number of leaves produced by V1 on sandy soil and V1 and V3 on sandy clay loam, as well as among the three varieties on sandy loam soils (Table 3). At the flowering stage, the leaf numbers of V1 on sandy soil differed significantly from those of V3 on sandy soil, V1 and V2 on sandy clay loam, and V3 on sandy loam. During the pod-setting stage, significant differences were noted in the leaf numbers produced by V3 planted on sandy loam soil compared to the numbers for V2 on sandy loam and V1 and V2 on sandy clay loam. Additionally, at maturity, significant differences in leaf numbers were observed between V2 on sandy clay loam and V1 and V3 on sandy soil, as well as V3 on sandy clay loam.

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Growth Stages		Variety/Treatment	Sandy	Sandy Clay Loam	Sandy Loam
Emergence		V1	9.00±1.00^{a}	4.00±2.00^{c}	5.00±2.00^{bc}
		V2	8.00±0.00^{ab}	7.00±1.00^{abc}	6.00±1.00^{bc}
		V3	7.00±0.00^{abc}	6.00±1.00^{bc}	5.00±2.00^{bc}
		LSD ($p < 0.05$)	3.04		
Flowering		V1	15.00±3.00^{a}	6.00±0.00^{c}	16.00±5.00^{a}
		V2	13.00±3.00^{ab}	10.00±2.00^{bc}	13.00±1.00^{ab}
		V3	7.00±2.00^{c}	12.00±1.00^{ab}	10.00±2.00^{bc}
		LSD ($p < 0.05$)	4.57		
Pod setting		V1	26.00±4.00^{ab}	10.00±6.00^{c}	19.00±9.00^{abc}
		V2	22.00±12.00^{abc}	10.00±2.00^{c}	15.00±5.00^{bc}
		V3	26.00±7.00^{ab}	28.00±9.00^{ab}	30.00±1.00^{a}
		LSD ($p < 0.05$)	14.98		
Maturity		V1	34.00±5.00^{a}	20.00±4.00^{ab}	21.00±7.00^{ab}
		V2	22.00±8.00^{ab}	14.00±6.00^{b}	28.00±1.00^{ab}
		V3	31.00±4.00^{a}	32.00±13.00^{a}	29.00±11.00^{ab}
		LSD ($p < 0.05$)	28.17		

Table 3. Mean and Standard Deviation of Number of Leaves of Legume Varieties at Different Growth Stages

**Values with the same superscripts are not significantly different. V1 is variety 1 of cowpea (sampea 14), V2 is variety 2 of cowpea (sampea 17), and V3 is a variety of soybean (TGX 1465-1D). LSD is Least Significant Difference.*

3.2.3. Leaf Area Index

Leaf area is a critical growth parameter that serves as an indicator of both leaf canopies and the extent of soil coverage by leaves. It plays a significant role in influencing water evaporation from the soil surface and transpiration from leaf surfaces. Table 4 presents the estimated mean values of the leaf area indices (LAI) for the various legume varieties grown on three distinct soil textures.

During the emergence stage, the LAI of the legume varieties ranged from 0.015 to 0.021, and these ranges did not exhibit statistically significant differences. Notably, V1 cultivated on sandy clay loam soil displayed the highest LAI (0.021), while the same V1 planted in sandy clay loam had the lowest LAI. As the flowering stage approached, the LAI range expanded from 0.015 (V3 on sandy clay loam) to 0.027 (V1 on sandy soil), with these two values being significantly different. This suggests that, despite having a high number of leaves at this growth stage, these leaves had relatively smaller surface areas, resulting in smaller canopies and LAI. During the pod-setting phase, V1 planted on sandy soil exhibited the highest LAI (0.108), while V1 planted on sandy clay loam had the lowest LAI (0.027). This significant difference in LAI was observed between V1 on sandy soil and V3 on sandy soil, as well as between V1 and V3 on sandy clay loam and V3 on sandy loam soil.

At maturity, the highest LAI was recorded for V1 planted on sandy soil, whereas V3 planted on sandy clay loam and sandy loam exhibited the lowest LAI values (Table 4). Consequently, the LAI of V1 on sandy soil differed significantly from that of all other legume varieties on different soil textures, except for V2 on sandy soil and sandy loam soil. In summary, it appears that legume varieties V1 and V2 had better LAI on sandy soil compared to the other soil textures.

Growth stages	Variety/Treatment	Sandy	Sandy Clay Loam	Sandy Loam
Emergence	V1	0.021 ± 0.01^{a}	0.015 ± 0.005^{a}	0.018 ± 0.01^{a}
	V2	0.025 ± 0.01^{a}	0.017 ± 0.002^{a}	0.016 ± 0.004^{a}
	V3	0.023 ± 0.01^{a}	0.018 ± 0.004^{a}	0.018 ± 0.001^{a}
	LSD ($p < 0.05$)	0.012		
Flowering	V1	0.027 ± 0.002^{a}	0.017 ± 0.000^{ab}	0.017 ± 0.00^{ab}
	V2	0.015 ± 0.010^{b}	0.021 ± 0.004^{ab}	0.021 ± 0.003^{ab}
	V3	0.018 ± 0.010^{ab}	0.015 ± 0.002^{b}	0.019 ± 0.003^{ab}
	LSD ($p < 0.05$)	0.010		
Pod setting	V1	0.108 ± 0.007^{a}	0.027 ± 0.009^{c}	0.063 ± 0.026^{abc}
	V2	0.096 ± 0.085^{ab}	0.045 ± 0.011^{abc}	0.063 ± 0.036^{abc}
	V3	0.036 ± 0.008^{bc}	0.031 ± 0.0160^{c}	0.041 ± 0.002^{bc}
	LSD ($p < 0.05$)	0.064		
Maturity	V1	0.131 ± 0.016^{a}	0.040 ± 0.002^{cd}	0.063 ± 0.022^{bcd}
	V2	0.101 ± 0.082^{ab}	0.042 ± 0.020^{bcd}	0.100 ± 0.005^{abc}
	V3	0.040 ± 0.010^{bcd}	0.031 ± 0.016^{d}	0.032 ± 0.007^{d}
	LSD ($p < 0.05$)	0.061		

Table 4. Mean and Standard Deviation of Leaf area index of Legume Varieties at Different Growth Stages

**Values with the same superscripts are not significantly different. V1 is variety 1 of cowpea (sampea 14), V2 is variety 2 of cowpea (sampea 17), and V3 is a variety of soybean (TGX 1465-1D), LSD is Least Significant Difference*

3.3. Crop Water Use and Crop Coefficients

Tables 5 and Figure 3 present data on water consumption and resulting crop coefficients, respectively, for each legume variety. Detailed data on actual crop water use, reference evapotranspiration, and crop coefficients are presented in Supplementary Table 1. During the initial season, it was observed that V3 planted on sandy loam soil had the highest water consumption, followed by V2 on sandy and V2 on sandy loam soils. In contrast, V2 on sandy clay loam exhibited lower water consumption compared to the other two legume varieties on the same soil. The water use for V1, V2, and V3 ranged from 47.7 mm/m to 583.55 mm/m across the three soil textures.

Growth stages	Variety/Treatment	Sandy	Sandy Clay Loam	Sandy Loam
Initial Season	V1	59.08 ± 2.36^{abc}	67.70 ± 1.98^{abc}	$48.93 \pm 1.9.2^{bc}$
	V2	90.03 ± 2.56^{ab}	47.70 ± 2.56^{c}	90.11 ± 2.56^{ab}
	V3	57.17 ± 0.51^{abc}	44.68 ± 1.13^{c}	93.90 ± 3.43^{a}
	LSD (p < 0.05)	41.44		
Mid-Season	V1	454.74 ± 10.78^{abc}	583.55 ± 10.90^{a}	346.42 ± 5.63^{c}
	V2	352.04 ± 2.80^{bc}	422.41 ± 3.23^{abc}	442.23 ± 8.28^{abc}
	V3	391.75 ± 3.80^{abc}	445.11 ± 14.07^{abc}	$546.59.2 \pm 18.62^{ab}$
	LSD (p < 0.05)	195.10		
Late Season	V1	90.75 ± 2.21^{a}	59.55 ± 1.23^{a}	90.72 ± 0.13^{a}
	V2	70.08 ± 3.88^{a}	46.00 ± 2.63^{a}	93.83 ± 4.97^{a}
	V3	84.80 ± 2.01^{a}	68.27 ± 2.97^{a}	41.47 ± 1.34^{a}
	LSD (p < 0.05)	55.43		

Table 5. Mean and Standard Deviation of Actual Evapotranspiration by Legume Varieties at Different Growth Stages (mm)

**Values with the same superscripts are not significantly different. V1 is variety 1 of cowpea (sampea 14), V2 is variety 2 of cowpea (sampea 17), and V3 is a variety of soybean (TGX 1465-1D), LSD is Least Significant Difference*

At the initial season, legumes grown on sandy and sandy loam soils consumed more water than those on sandy clay loam soil. The larger pore spaces in sandy and sandy loam soils, compared to sandy clay loam, allowed for sufficient water release to the atmosphere. The permanent wilting point (PWP) of sandy soils is thus below the threshold PWP of other soil textural classes. Consequently, more water applications may be needed to meet the crop water requirement on sandy soils during the initial season when the soil surfaces were still bare and uncovered[39][40][41][42]. Statistically, significant differences were observed in water consumption at the crops' initial stages, particularly between V3 on sandy

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loam soil and V2 on sandy clay loam soil, as well as between V3 on sandy loam soil and V3 on sandy clay loam soil (Table 5).

During the mid-season, a noticeable increase in water consumption was observed for all three legume varieties compared to the initial stages. The variety V1 planted on sandy clay loam exhibited the highest water consumption (583.55 mm/m), while the lowest water consumption was recorded for V1 on sandy loam soil (346.30 mm/m). At this stage, significant differences in water consumption were observed between V1 on sandy clay loam soil and the following plots: V3 on sandy soil and V1 on sandy loam soils.

During the late season, typically characterized by pod maturation, water consumption rates for all three varieties decreased compared to the mid-growth stage. In this late season, the crops experienced reduced transpiration, resulting in significantly lower water usage compared to the mid-season. This decrease in transpiration rates can be attributed to physiological leaf deterioration, aging, and leaf shedding[38]. Notably, the water consumption of legumes at this stage was not significantly different from one soil texture and legume variety to another.

The FAO-56 crop coefficient approach, commonly utilised for estimating crop water requirements under well-watered conditions, stands as the standard method widely adopted for irrigation management, particularly for irrigation scheduling[33]. According to this approach, K_c tends to increase as the crop develops, reaching maximum values when the crops are fully matured[43]. The findings of this study also revealed a gradual increase in K_c values from the initial growth stage to the developmental and mid-season stages, followed by a decrease in the late-season K_c. This pattern of increasing crop coefficients reflects the impact of crop growth, development, and physiological processes on water consumption and evapotranspiration[14].

According to Allen et al.[33], K_c values of 0.4, 1.15, and 0.55 were determined for legumes during the initial, mid-season, and late-season, respectively. However, in this study, the averages of K_c obtained are 0.69, 1.46, and 0.78 for the initial, mid-season, and late-seasons, respectively. Specifically, legumes grown on sandy soils had an average K_c of 0.71, 1.32, and 0.90 for the initial, mid-season, and late-season stages, respectively. On sandy clay loam soils, the average K_cs are 0.54, 1.59, and 0.65, and on sandy loam soils, they are 0.82, 1.47, and 0.79, respectively (Figure 3). The slight variations in K_c observed can be attributed to differences in climate and soil characteristics, as noted by Kullberg et al.[44] and Jamshidi et al.[23].

It's worth noting that the Kc values obtained for V1, V2, and V3 closely align with those estimated by Alla-Jabow et al.[35] for faba bean, chickpea, and common bean in a semi-desert climatic region with very hot conditions in Ed-Damer, Sudan. Alla-Jabow et al.[35] estimated values of 0.33, 0.26, and 0.52 for faba beans, chickpea, and common bean, respectively, during the initial stages. During the mid-season, the reported K_c values were 1.08, 1.22, and 1.07 for faba beans, chickpea, and common beans, respectively. The K_c was observed to have increased from the initial stage. However, during the late season, the K_c decreased to 0.60, 0.52, and 0.52, in the same order. During the initial stage, the averages of K_c for V1, V2, and V3 are 0.55, 0.71, and 0.81, respectively. At the mid-growth stage, the averages of K_c are 1.48, 1.30, and 1.60 in the same order, and during the late season, the averages of K_c are 0.79, 0.68, and 0.86, respectively (Figure 3). These coefficients depict variations in crop water requirements and transpiration rates at different growth stages, on different soil textures, and among different legume varieties.

In a similar study conducted by El-Noemani et al.[45] on irrigated varieties of *Phaseolus vulgaris L.* in the Nile Delta clay loam old alluvial soil, the initial K_c ranged from 0.63 to 0.64 for the Bronco variety. The K_c ranges of 0.82 to 0.87, 0.99 to 1.09, and 0.80 to 0.95 were obtained for the flowering, pod-setting, and maturity stages, respectively, at varying levels of water applications (40%, 60%, and 80%). Furthermore, K_c value ranges of 0.59 to 0.61, 0.78 to 0.98, 1.07 to 1.19, and 0.73 to 0.88 were obtained for the Contender variety at flowering, pod-setting, and maturity stages at varying levels of water application.

4. Conclusions

This study aimed to investigate water usage and crop coefficients of legumes cultivated on three distinct soil textures in southern Nigeria, with the goal of improving crop and water management practices. The findings indicated that legume water consumption was highest during the mid-season, influenced by various factors such as climatic conditions, months, and seasons of the year. Legume varieties planted on sandy clay loam soils exhibited the highest average actual evapotranspiration, indicating greater water usage or soil water depletion on this soil type. Notably, crop coefficients estimated for legumes grown on sandy loam were higher than those obtained for sandy and sandy clay loam soils, particularly during the mid and late seasons. The soybean variety V3 consistently displayed higher average K_c across the soil types than the two cowpea varieties, V1 and V2, at all growth stages.

Although only one trial of this experiment was conducted, the findings provide major information on the K_c of legumes. It is recommended that the coefficients obtained from this study be re-affirmed within and outside the study area, especially by repeating the study during several planting seasons. Furthermore, the use of machine learning models for the estimation of ET_p and ET_c, and thus K_c, is also recommended. Less human-dependent methods should be employed to monitor changes in soil moisture content over time in such studies, in order to ensure the collection of error-free data.

The implications of this study are significant, especially for irrigation engineers, agriculturists, soil scientists, and environmentalists. The findings can inform improved irrigation scheduling, water management practices, and enhanced crop and water productivity in agriculture, particularly in regions with a climate similar to that of southern Nigeria.

Data Availability Statement

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Author Contributions

Conceptualization: B.F.S; methodology: B.F.S and D.I.U; software: B.F.S; data collection and analysis: B.F.S. and D.I.U; validation: B.F.S and R.S; formal analysis: B.F.S and D.I.U; investigation: B.F.S, D.I.U, R.S.; resources: B.F.S, D.I.U; data curation: B.F.S and R.S; writing-original draft preparation: D.I.U and R.S; writing-review and editing: B.F.S; visualization: B.F.S and R.S; supervision: B.F.S; project administration: B.F.S and R.S.

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