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Optimization of a Capillary Irrigation System for Field Application

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Abstract

Subsurface micro-irrigation systems are widely considered as a promising means to increase water use efficiency in agriculture. An economical, less laborious, and water-efficient type of capillary irrigation system (CIS) was developed. Optimisation of this CIS for greater efficiency requires adequate knowledge of the accurate surface wetted radius under different capillary node sizes and soil textures. A point source type for the different capillary node sizes (12.7 mm, 19.1 mm, 25.4 mm, and 50.8 mm diameter) installed in rectangular containers were studied under six soil types (Itagunmodi series (Ferrasols), Egbeda series (Lixisols), Oba series (Cambisols), Iwo series (Lixisols), Apomu series (Cambisols) and Fine sand as control), and compared with hand irrigation (watering can) in a screen house experiment. Soil moisture spread around the capillary nodes was monitored, and the empirical equations for predicting soil surface wetted radius for each capillary node size were developed and verified in the field. The results showed that soil wetted radius increases with an increase in the soil clay content, and the soil type with the highest clay proportion (18%) generated the maximum wetting front. Sorptivity correlated with soil moisture spread, but the consistency of the wetted area depended on the soil clay content. Capillary node sizes 12.7 mm and 50.8 mm diameters performed better and enhanced soil water distribution across different soil types compared to other capillary node sizes due to their narrow-node and pore-number effects, respectively. The lateral spacing of these node sizes per unit land area for optimal performance can be guided by the models developed in this study.

Keywords: Capillary irrigation; Soil moisture; Empirical equation; Soil types; Wetted radius.

1. Introduction

Irrigation water requirements set a competitive demand for the available water resources among several sectors, including domestic, thermoelectric, industries, and aquaculture. In 2017, UNESCO recorded that agriculture consumes around 70% of global freshwater as irrigation, thus limiting water availability for other purposes [1]. Innovations and techniques that improve water use efficiency within the agricultural system are essential in securing water for other essential purposes [2]. As part of the efforts to make water available for human and other purposes, several researches now focus on agriculture with a particular interest in reducing water losses through crop water productivity and water use efficiency. Some of these water-saving irrigation techniques are now being implemented to save water in irrigated agriculture, such as capillary irrigation systems (CIS) and drip irrigation systems. The drip irrigation system is a relatively expensive micro-irrigation system and unaffordable for many rural farming communities in developing countries due to the high costs of energy and the system itself [3]. On the other hand, CIS is a sub-irrigation method that delivers water to plant roots through capillary actions, and they are widely used for growing ornamental plants and vegetables, mostly in containerised systems [4,5].

The operational principle of CIS is the capillary mechanism of supplying water to the plant root zone. Various designs of CIS have been documented in the literatures, such as capillary mats, capillary wicks, and ebb and flow systems that operate on capillarity principles [5]. CIS has been recognised to increase irrigation water-use efficiency. A study reported higher quality yield and water-use efficiency of greenhouse peppers in a trial using the capillary flow from a water interface medium into the soil [6]. A recent review of the widely used traditional CISs for growing crops suggests that CIS can increase crop yields, reduce water consumption, and circumvent the leaching of potentially harmful agro-chemicals into the environment [5].

In recent years, CIS has been gaining wider application in African countries and research is ongoing to commercialise appropriate designs suitable for specific crops and soil conditions based on locally available materials. For example, locally available wick material has been used to develop capillary-based wick irrigation systems for producing ornamental potted plants and vegetables in Kenya [5,7]. Similarly, a scalable type of CIS was developed to boost vegetable production in southwestern Nigeria [8]. However, most of the reported CISs have only been optimized for use in pot and screen house experiments.

A type of CIS developed in Obafemi Awolowo University in Nigeria is field operational and scalable, and has been used to produce leafy *Amaranthus viridis* in humid forest and savanna agro-ecological zones of southwestern Nigeria [8]. This CIS operates on the natural principle of capillary rise of water from a buried reservoir (made of PVC pipe) into the plant root zone through a conducting sand-bed. The CIS consists of a capillary node inserted at the centre of a lateral reservoir sealed at both ends (Figure 2). The capillary node is filled with graded soil material that enables it to conduct and filter water from a lower reservoir. The spread of water in the soil under this CIS is often modulated by some soil physical properties related to sand, silt, and clay proportion, the amount of soil organic matter and the energy gradient within the soil [8–10]. This novel CIS compared favourably better than the traditional sprinkler system under different fertiliser applications in a field study [8]. It produced higher fresh vegetable yield than all other treatments and saved an average of 1.1 million litres and 6 million litres of water per ha in the savanna and forest locations, respectively, per cropping season. However, water application efficiency and distribution uniformity of the CIS remain inconsistent under different soil types. The key influencing component of the CIS is the capillary node, which conducts water from a buried reservoir into the crop root zone. Nevertheless, the capillarity of the node is often affected by its diameter, while the water transmission pace and distribution within a localized wetted zone depends on the soil textural properties. As such understanding the interaction between different capillary node sizes and soil wetting pattern under different soil textural classes is essential to improve the suitability of the CIS for use under various soil conditions in southwestern Nigeria.

The wetting pattern dimensions under the CIS can be modelled to design a CIS suitable for use under different soil types. For instance, previous studies have empirically modelled the wetting pattern dimensions under drip irrigation system as a function of application rate, application time, saturated hydraulic conductivity, initial moisture content, bulk density, and percentages of sand, silt, and clay content of soil [11–14]. Therefore, the wetting pattern dimensions under the CIS are assumed to be affected by many factors related to soil physical properties such as sorptivity, hydraulic conductivity, bulk density, and initial soil moisture content [13,14]. Besides, some other factors are related to CIS, such as the node sizes, the spacing between the capillary nodes and the laterals [5,8]. In this study, we hypothesis that soil wetted radius under the CIS is largely controlled by soil properties and capillary node size used in the CIS rather than the quantity of the conducting material (graded soil) filled into the CIS nodes. Therefore, the objectives of this study were to develop empirical models that can adequately predict soil wetting radius under this CIS using different capillary node sizes and soil properties; and to determine the most effective capillary node sizes across different soil textures. These are to improve the application efficiency of this novel CIS.

2. Materials and methods

2.1 Study area

The study was carried out at two locations: (i) the Screenhouse and (ii) the Teaching and Research Farm, Obafemi Awolowo University, Ile-Ife, Osun State in Southwestern

Nigeria. The Screenhouse lies approximately within Latitudes 7^{o} 31' 23"N & 7^{o} 31'24"N and Longitudes 4^{o} 31'41 "E & 4^{o}31'43 "E while the field experiment was carried out at the Obafemi Awolowo University Teaching and Research Farm, which lies between approximately Latitudes 7^{o} 32'N & 7^{o} 33'N and Longitudes 4^{o} 32'E & 4^{o} 34'E with an altitude of about 244 m above mean sea level. It is in the rainforest agroecology of Southwestern Nigeria with a mean annual rainfall of about 1400 mm, which is bimodally distributed with peaks in June and September, while the mean temperature ranges between 28^{0}C to 34^{0}C [15].

2.2 Soil samples collection

Bulk topsoils (0–15cm) were collected from six soil types with varying textures; Itagunmodi series (sandy clay) classified as Ferrasols, Egbeda series (sandy loam) classified as Lixisols , Oba series (sandy loam) classified as Cambisols, Iwo series (sandy loam) classified as Lixisols [16–19] and Apomu series (sandy loam) classified as Cambisols[17] at a depth of 0-15 cm (Figure 1) and fine sand was an erosion-washed sand deposit collected at Obafemi Awolowo University Parks and Garden, it was passed through a 2 mm sieve before being used as control. The soils were used to fill the capillary irrigation containers directly without sieving except for fine sand (Figure 2).

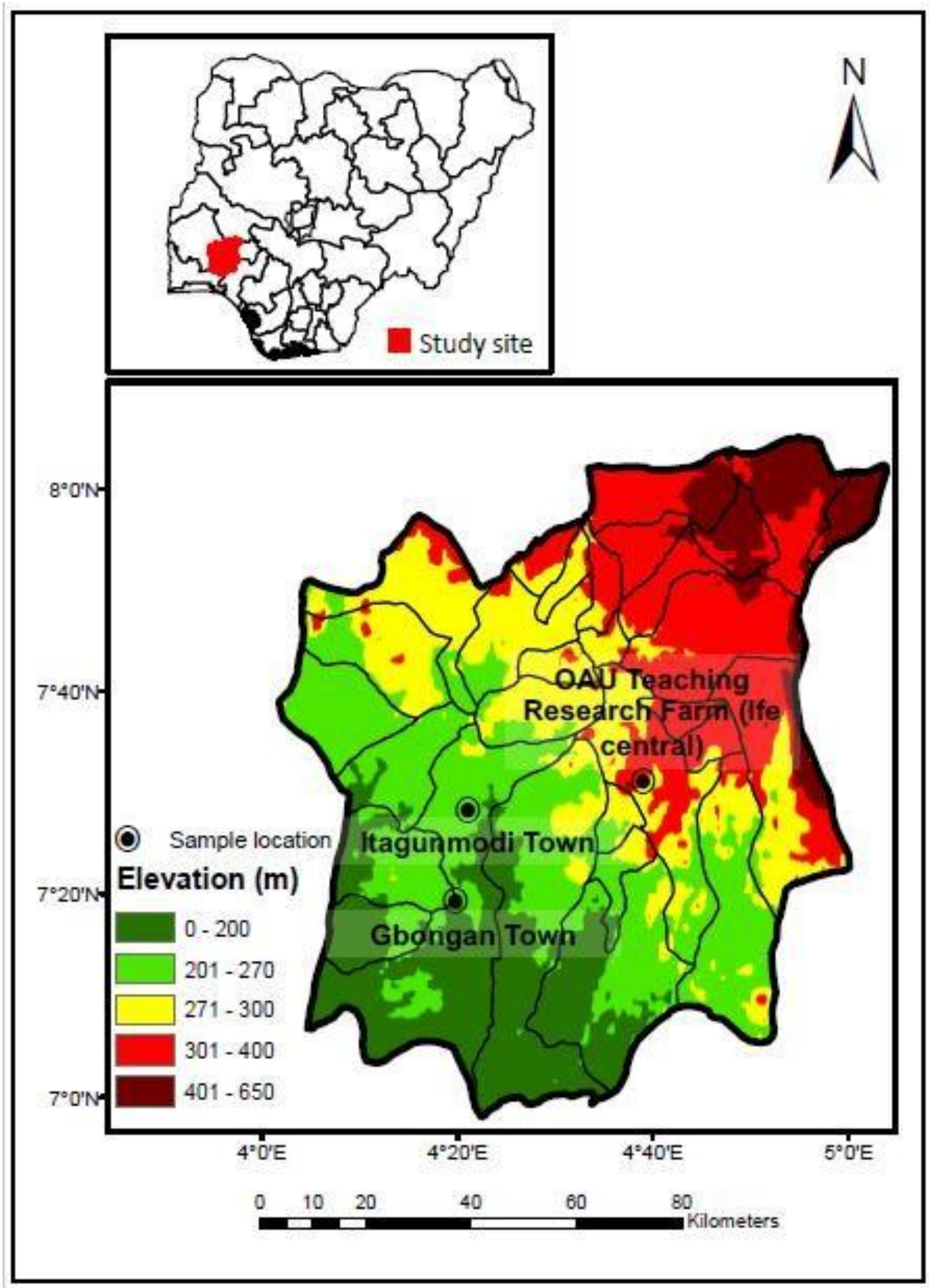
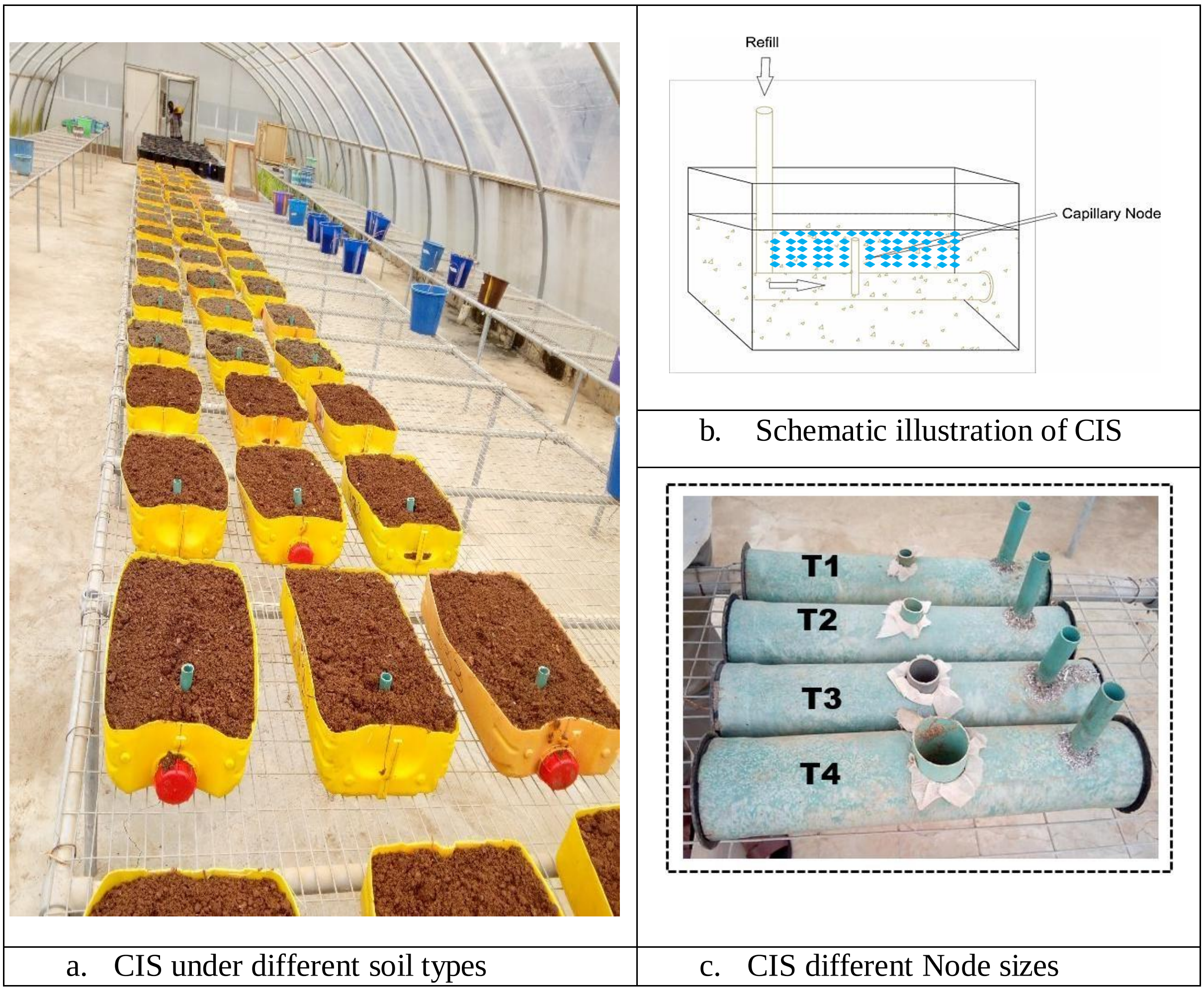


Figure 1. Soil sampling locations for the selected soil series as referenced in Southwest Nigeria [20]. Egbada and Oba series were collected at the upper slope and lower slope (Hill wash) of the reference Egbeda association at Obafemi Awolowo University teaching and research farm. Iwo and Apomu series were collected from middle and lower slope of the referenced Iwo association in Gbongan Town. Itagunmodi series was collected from Itagunmodi Town.



b. Schematic illustration of CIS

a. CIS under different soil types

c. CIS different Node sizes

Figure 2. Capillary Irrigation system (CIS) setup and different capillary node sizes (T4: 50.8 mm, T3: 25.4 mm, T2: 19.1 mm, and T1: 12.7 mm diameter).

The soils in the experimental setup were compacted close to the representative field bulk density (between 1.4–1.6 g cm^{-3}) to simulate the field conditions. Samples for laboratory analyses were taken from the bulk soil of each soil type before and after irrigation; the samples were air-dried and passed through 2 mm sieve. The samples were analysed for sorptivity and unsaturated hydraulic conductivity after the experiment using a mini-disk infiltrometer (Decagon Devices, Inc., Pullman, W). The particle size distribution, field capacity (FC), porosity, and organic carbon content of the soils were determined according to standard methods detailed under laboratory analysis [21,22].

2.3 Construction and installation of the capillary irrigation

A water and irrigation screenhouse study was carried out using a soil container of internal dimensions (44 cm length, 23 cm width, and 14 cm depth). Polyvinyl chloride (PVC) cylindrical pipes of different diameters (50.8 mm, 25.4 mm, 19.1 mm, and 12.7 mm) were used as the capillary nodes, while the lateral reservoir was a PVC pipe of 76 mm diameter (Figure 2). Capillary node sizes 50.8 mm, 25.4 mm, 19.1 mm, and 12.7 mm diameter were used and denoted as T4, T3, T2, and T1, respectively. Each of the capillary nodes (T4, T3, T2, and T1) was covered with muslin cloth at the base and then filled with graded sand (layer of 25 % 0.1-0.5 mm, 50% of 1.0-2 mm erosion wash sand, and 25% of the soil type where the capillary irrigation is installed) as conducting material to support the capillary rise of water through the capillary node. The muslin cloth helps to prevent the graded sand packed inside the capillary nodes from leaking into the lateral reservoir. The capillary nodes were then installed at the centre of a 370 mm long larger diameter PVC pipe (81.9 mm diameter) which served as the buried water reservoir. The reservoir was sealed adequately at both ends to prevent water leakage, and in order to simulate a point source CIS, one capillary node was installed per reservoir (Figure 2c). Following that, each CIS was assembled and installed at the centre of a rectangular container, and the container was then filled with soil up to 10 cm mark above the capillary node and tapped to field bulk density.

2.3.1 Experimental setup

The experiment was a 6 by 5 factorial experiment laid out in Randomized Complete Block Design having three replicates. The six soil types were subjected to five irrigation methods. The total treatments were 90, of which 72 were tested under capillary irrigation of different node sizes and 18 under a traditional sprinkler system (watering can) as control. Bulk surface soil samples were collected from five soil series (Apomu series, Itagunmodi series, Egbeda series, Oba series, Iwo series, while fine sand served as a control) to fill these irrigation containers. The same volume of the reservoir was installed for the four node-sizes, and water was filled (through the “refill tube” Figure 2) to 85% of the reservoir volume (1200 ml) with a top-up every 48 hours to the 85% mark. The decision to use small reservoir size was constrained by the irrigation container size. Therefore, the top-up was necessary to prevent excess water depletion in the reservoir. It is worthy to note that a large reservoir size which can retain large volume of water is deployable in the field condition.

2.3.2 Monitoring of soil water distribution

The soil water contents at different distances from the capillary node position was monitored daily using a digital soil moisture meter (PMS 710 by Tsingtao Toky Instruments Co. Ltd.). It is a portable meter that measure the volumetric water content based on the dielectric and electric properties of the soil (with accuracy of ± 2% under non-saturated condition, resolution of 0.1 and instant response time). The moisture measurements were taken at 15 cm depths from the centre along the length and breadth of the rectangular container at the thirteen (13) designated points (at the centre of the rectangular container C, L1, and L2 = 10 cm and 20 cm left of C, R1, and R2 = 10 cm and 20 cm right of C, all along the length of the container respectively, Do1 and Do2 = 5 cm and 10 cm down of C, Up1 and Up2 = 5 cm and 10 cm up of C along the breadth respectively. EG1, EG2, EG3, and EG4 = vertexes of the rectangular container (Figure 3). The first phase of the experiment lasted six weeks. The irrigation was stopped for three weeks, then the second phase of the study began, and the irrigation was continued for one week. Further study was also carried out on the field using capillary irrigation treatments (T1= 12.7 mm, T2= 19.1 mm, T3= 25.4 mm, and T4= 50.8 mm node sizes) to monitor the spread of soil moisture at 10 cm intervals from the centre of the capillary node daily for five days (Figure 3).

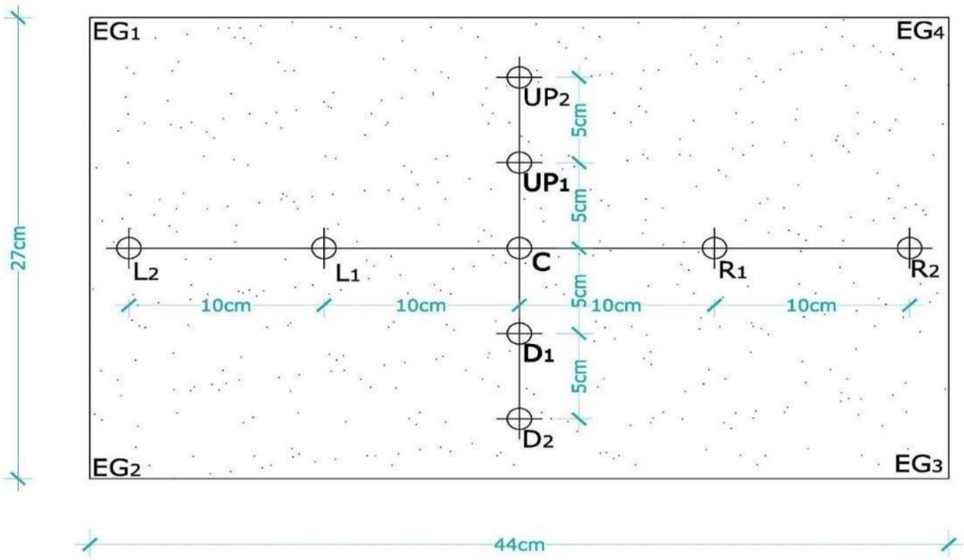


Figure 3. Designated points of monitoring soil moisture content in the capillary irrigation system setup**.** C= Center of the rectangular container, L1 and L2 = 10 cm and 20 cm left of C, R1 and R2 = 10 cm and 20cm right of C, D1 and D2 = 5 cm and 10 cm down of C, Up1 and Up2 = 5 cm and 10 cm away from C along the breadth respectively. EG1, EG2, EG3 and EG4 = vertexes of the rectangular container.

2.4 Laboratory analyses

Total porosity was estimated as the water content at saturation described by [22]. The gravimetric soil moisture content at field capacity was determined as described by Lowery et al. [21], while soil bulk densities were determined in the laboratory using a core sampler method [23,24]. The particle size distribution of the six soil types was determined in three (3) replicates using the modified hydrometer method [25,26] with a 0.2 M sodium hydroxide solution as the dispersing agent. The soil organic carbon was determined using the chromic acid digestion method (oxidation method) [27] as modified by Nelson and Sommers [28].

2.4.1 Unsaturated hydraulic conductivity

The unsaturated hydraulic conductivity of the soils was determined *in situ* at the Screenhouse using a decagon mini-disk infiltrometer at 2 cm suction. The instrument generated infiltration data, which were used to compute the unsaturated hydraulic conductivity using the method proposed by Zhang [29].

$$I = C_1\sqrt{t} + C_2 t \quad (1)$$

Where I is the cumulative water intake per unit area (ms^{-1}), t is time (s), C_1 ($\overset{\alpha}{m}$ s^{-1}) and C_2 (m $\mathrm{s}^{-\frac{1}{2}}$) are parameters related to hydraulic conductivity and sorptivity of the soil, respectively.

2.4.2 Soil sorptivity

The sorptivity of the soils (C_2) was obtained from the quadratic graph of the cumulative infiltration versus the square root of time (equation ii), as the coefficient of “x” [29].

2.4.3 Unsaturated hydraulic conductivity (K)

The unsaturated hydraulic conductivity (K) of the soil was computed using the relationship:

$$K = \frac{C_1}{A} \quad (2)$$

Where K is the unsaturated hydraulic conductivity (ms^{-1}), C1 is the slope of the curve of the cumulative infiltration versus the square root of time (as the coefficient of “x^2”), and A is the van Genuchten parameters for a given soil type under a particular suction rate and radius of infiltrometer disk (2.5 cm) was obtained from the tabulated Van Genuchten parameters for 12 soil texture classes for a 2.25 cm disk radius and suction values from 0.5 to 6 cm [30,31].

2.5 Statistical analyses

Data obtained for all the soil properties determined were subjected to Analysis of Variance using the Proc GLM procedure in SAS (SAS University Edition, 2018) to assess the performance of the capillary irrigations under the selected soil types, and were correlated with selected soil physical and chemical properties. Duncan's New Multiple Range Test was used to separate the means at $p < 0.05$ for significant treatments.

2.5.1 Modelling of wetted radius under capillary irrigation

The model structure for predicting horizontal wetted radius under capillary irrigation have been identified from similar studies on drip irrigation reported in the literature [11–14]. The experimental data obtained from the capillary irrigation experiment under different soil types were subjected to multiple regression analysis based on the identified model structure to generate the coefficients that characterise the empirical model. The empirical model was tested in linear, polynomial, and nonlinear forms. The best fit was found with the nonlinear form.

3. Results and discussion

3.1 Physical and chemical properties of the selected soil types

The particle size distribution and textural classes of the selected soil types are shown in Table 1. These results showed that all the selected soil series have a high percentage of sand fraction, which was above 70%, except for Itagunmodi series where the sand fraction was below 50%. The selected soil series, including Apomu, Itagunmodi, Egbeda, Oba, Iwo were classified as sandy loam, sandy clay, sandy loam, sandy loam, and sandy loam, respectively, according to USDA soil textural classification. Soil texture is an essential property of the soil that influences the nutrient retention and drainage capabilities of the soil. It is directly related to water-holding capacity, aeration, cation exchange capacity, and hydraulic properties. Thus, it is considered as the inherent attribute of the soil [32].

The chemical properties of the selected soil types are also presented in Table 2. The pH of the soil series in $CaCl_2$ falls between medium acidic (Oba, Egbeda, Iwo and Apomu) to very slightly acidic (Itagunmodi), while the fine sand is very slightly alkaline as classified by [33,34]. The acidic nature of the soils could be partially linked to the inherent nature of their parent material [20], and the loss of basic cations through agricultural practices, and the leaching of exchangeable bases. This is because the soils of the region were formed from acidic parent material, coupled with the effects of heavy seasonal rainfall that remove basic cations and persistent use of mineral fertiliser that influence the pH of the soil [20,35]. Similarly, the soils were significantly different in their electrical conductivities (EC) but far below the critical value capable of impairing plant productivity.

Table 1. Some physical of the selected soil types

Soil types	Sand	Silt (gkg^{-1})	Clay	Textural Class
Fine sand	930	10	60	Sand
Apomu	760	140	100	Sandy Loam
Itagunmodi	460	360	180	Sandy Clay
Egbeda	730	160	110	Sandy Loam
Oba	700	170	130	Sandy Loam
Iwo	730	140	130	Sandy Loam

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Adepetu et al. [33] classified EC values ≥ 400,000 µSm^{-1} to be saline, which can adversely affect plant productivity. These results agree with previous studies conducted under similar soil types, land use and climatic conditions [36,37].

The organic carbon (OC) of the studied soils were not significantly different. OC as an index of organic matter helps improve soil structure through the cementation process, which brings about change in soil hydraulic properties and directly affects soil aggregation, and the capacity of the soils to store water [38–41]. The mean comparison of some chemical properties of the selected soil types before and after irrigation is presented in Table 2. The pH of the selected soil types before and after irrigation was not significantly different, while the electrical conductivity (EC) of the soil solution was significantly higher after irrigation. The increase in soil EC after irrigation could have resulted from the irrigation water used for the study, which contains some level of soluble salt (0.976 µS/m) that contributed to the differences observed since evaporation from soil surface leaves salt deposits behind. This however, is not of a concern in the study area as heavy rainfall will flush the dissolved salts down the soil profile.

Table 2. Mean comparison of some chemical properties of the selected soil types before and after irrigation

Soil types	pH ($CaCl_2$)		EC (μSm^{-1})		OC (gkg^{-1})	
	Before	After	Before	After	Before	After
Fine sand	7.34±0.13a	7.07±0.03a	28.4±0.65b	132±0.60a	12.99±2.10a	6.36±0.57a
Apomu	5.45±0.14a	5.46±0.08a	22.9±00b	290±0.50a	13.89±3.50a	13.90±0.34a
Itagunmodi	6.25±0.02a	5.72±0.02a	13.9±0.55b	776±1.35a	25.84±2.43a	30.26±0.69a
Egbeda	5.66±0.14a	5.89±0.05a	33.0±0.45b	499±0.50a	19.09±0.60a	20.52±0.26a
Oba	5.22±0.02a	5.62±0.05a	30.9±0.25b	407±11.0a	17.01±0.26a	16.36±0.39a
Iwo	5.74±0.02a	5.79±0.07a	30.2±0.05b	351±17.0a	14.42±0.67a	12.60±0.26a

EC= Electrical conductivity, OC= Organic carbon. According to Duncan's Multiple Range Test, means in the same row under the same property with the same alphabets are not significantly different at 0.05 level of probability.

The significant variation in the EC of the soil after irrigation substantiated several previous findings [42–44] that sub-irrigation could result in elevated EC values in the upper regions of container medium compared to overhead irrigation. This suggests that proper salinity check of irrigation water will prevent salinity hazards in irrigated crops. In the humid tropics of Nigeria, the problem of salinity is not envisaged as the prevailing high rainfall will flush salt down the profile.

The unsaturated hydraulic conductivity (K), porosity, field capacity, bulk density, and sorptivity were significantly different in each of the soils (Table 3). The unsaturated hydraulic conductivity (K) of fine sand was significantly higher than others, while Apomu, Itagunmodi, Egbeda, Oba, and Iwo were statistically the same. This reflects that water moves faster through the fine sand in unsaturated conditions than any other selected soil types. This result corroborated several findings [45–47] that soil hydraulic properties are influenced by texture, structural characteristics, and organic matter content of the soil. A similar trend was also observed for sorptivity. Itagunmodi series had the highest per cent organic carbon and clay content. This could be directly linked to the high FMC and porosity observed for this soil. Wösten et al. [48] reported that soil water retention property is a complex function of the soil structural composition and organic matter content. Likewise, clay and organic matter positively correlated with the increasing capacity of soil to retain water irrespective of texture [49–51].

Table 3. Some physical properties of the selected soil types

soil series	K (mh^{-1})	Porosity (%)	FC (%)	ρb (m^{-3})	Sorptivity (cm^{-2})
Fine sand	142.84±0.77a	44.13±1.94d	35.97±2.02b	1.59±0.05a	0.4353±0.02a
Apomu	24.30±0.15b	59.80±2.84c	41.33±4.01a	1.17±0.05cd	0.1363±0.02b
Itagunmodi	21.1±0.83b	63.33±11.21a	42.91±10.9a	1.13±0.39d	0.1499±0.04b
Egbeda	20.27±0.16b	60.87±5.51c	37.60±5.51b	1.28±0.07b	0.1432±0.01b
Oba	16.15±0.10b	62.97±3.82b	31.30±3.82c	1.20±0.08c	0.1567±0.01b
Iwo	25.59±0.17b	62.01±4.58bc	32.29±4.50c	1.29±0.06b	0.2172±0.01b

Note: - Means in the same column with the same alphabets are not significantly different at 0.05 level of probability according to Duncan's Multiple Range Test. K= unsaturated hydraulic conductivity, FC= Field Capacity, Db= Bulk density

Similarly, many previous studies [52–55] reported that various soil physical properties such as texture and structure affect the spread of water from drip sources. A similar trend was observed for organic carbon content and the clay proportion (Tables 1 and 2). Itagunmodi has the highest organic carbon content (25.48 g/kg) and clay proportion (18%). Clay proportion and soil organic matter content are important soil properties influencing water holding and distribution in soil [56].

3.2 Effects of the CIS node sizes on soil water distribution

Figure 4 depicts the spatial distribution of soil water among the different soil types measured at the designated points. The highest spread of soil water was recorded in Itagunmodi series with an approximately 38 cm radius from the centre of the irrigation container. The spread of soil moisture in Oba and Egbeda series were next in rank, and these were followed by Iwo series, then Apomu series. Fine sand had the least spread with the overall least moisture content value (19.81%). The variability observed in moisture distribution across the designated points under the selected soil series could be due to differences in organic carbon content and clay proportion. Tijani & Oyedele [57] demonstrated that temporal variation in soil water content mainly depends on the weather, while spatial variation is related to the clay content of the soil.

Figure 5 illustrates the effects of the irrigation types on soil water distribution measured across the (13) designated distances (points) on the selected soil series and fine sand tested under the five irrigation methods. From the results, each of the irrigation methods (S, T1= 12.7 mm, T2 = 19.1 mm, T3 = 25. 4 mm, and T4 = 50.8 mm diameter node capillary irrigation) supplied water differently at all the designated points except at the centre of the irrigation container (point C) and 10 cm from the centre along the length of the irrigation container (point L1). Irrigation methods T1 (12.7 mm diameter capillary node size) and T4 (50.8 mm diameter node) had the highest water spread (approximately 30 cm soil wetted radius) across all the designated points of measurement. The overall better performance of irrigation method T1 across the designated points of measurement could be linked to the small diameter (12.7 mm diameter capillary node size) of its cylindrical capillary node that favoured the capillary rise of

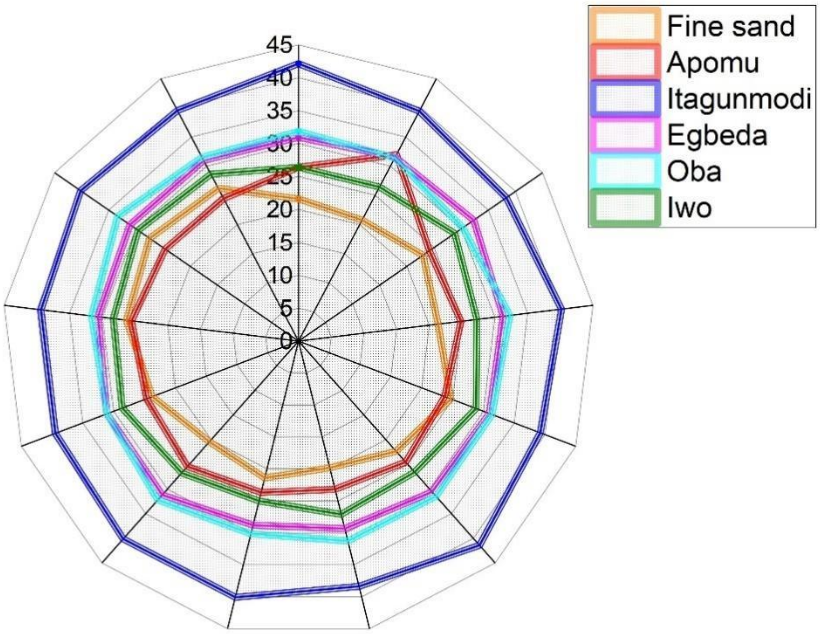

Figure 4. Soil wetting pattern (m^3/m^3) under capillary irrigation of different node sizes as affected by soil types. 1= fine sand, 2= Apomu, 3= Itagunmodi, 4= Egbeda, 5= Oba, and 6= Iwo series. (0-45 represent the volumetric water content (%) along the fixed measurement points. C= Center of the capillary node (water outlet).

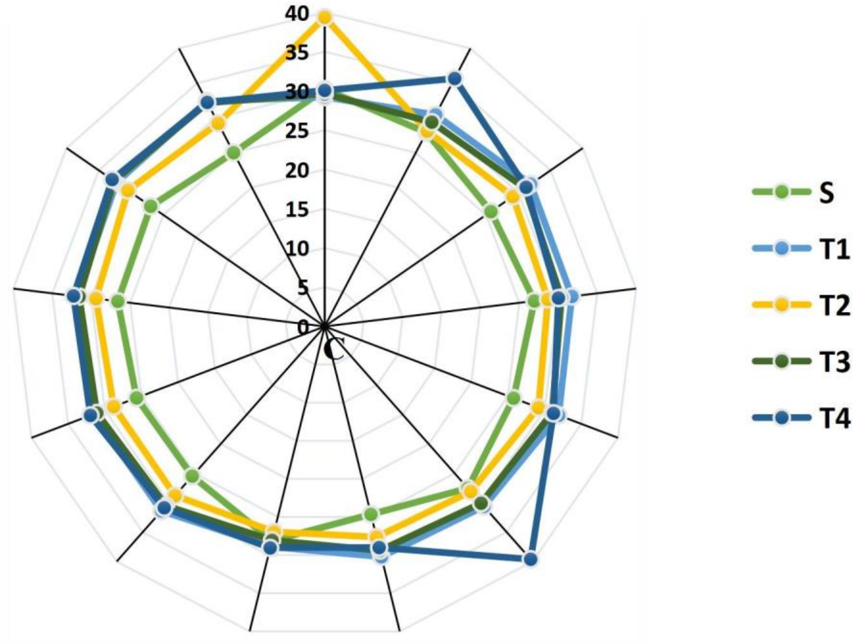

Figure 5. Effects of the irrigation methods on soil water distribution measured across the designated distances (points) on the selected soil types tested under the five irrigation methods. S=Sprinkler irrigation, T1= 12.7 mm, T2 = 19.1 mm, T3 = 25. 4 mm, and T4 = 50.8 mm diameter node capillary irrigation. 0-40 represent the volumetric water content (%) along the fixed measurement points. C= Center of the capillary node (water outlet).

water. These results validated Jurin' law of capillary rise [58], which states that the height of a capillary column of a liquid at a particular temperature is inversely proportional to the diameter of the tube, provided the tube radius is smaller than the capillary length. Zachary [59] also noted that capillary forces influence how far water rises in a tube depends on the tube size (diameter) and analogous to the increase in capillary force as soil pore size decreases. It is worthy to note the similarly high wetted radius observed under capillary node size T4 with a bigger diameter (50.8 mm), this can be attributed to micropore-induced capillary forces which drive water upward in the capillary tubes [60]. This high capillarity is expected in capillary node T4 due to the larger content of conducting material (graded soil) packed inside the node. As such, micropore-induced capillarity matched the spread of wetness linked to narrow-node effects of the smallest diameter capillary node size T1 (12.7 mm). Further, the average wetted radius of capillary irrigations (T1, T2, T3, and T4) across different soil types was higher compared to sprinkler irrigation (S). This is because a sprinkler irrigation system instantaneously exposes all the irrigation water to evaporation while capillary irrigation conserves water in its buried reservoir and releases it into the upper soil in response to evaporative demand. In a sprinkler irrigation study, Zazueta [61] noted that the amount of water evaporating during sprinkler operation depends on the climate demand, the time available for evaporation to occur, and the surface area of the water droplets. Likewise, the soil surface crusting caused by the impact of water droplets on the soil surface when using sprinkler irrigation (S) could lower water infiltration into the soils, thereby exposing free water evaporation [62].

3.3 Performance of the capillary node sizes tested under the selected soil types

The performance of each of the capillary node sizes across the selected soil types is shown in Figure 6. The capillary node size 25.4 mm diameter (T3) performance was significantly higher than other irrigation types under soil 1 (fine sand). The performance of capillary node sizes 12.7 mm (T1), 25.4 mm (T3), and 50.8 mm (T4) diameters were not significantly different under soil 2 (Apomu soil series), although capillary node size T1 (12.7 mm diameter) supplied more water. Capillary node sizes were not significantly different in their performances under soil 3 (Itagunmodi soil series), but 19.1 mm (T2) and 50.8 mm (T4) supplied more water. Capillary node size T1 (12.7 mm diameter) performance was significantly higher than other irrigation types under soil 4 and 5 (Egbeda and Oba soil series), while the performances of 12.7 mm (T1), 50.8 mm (T4), and S were not significantly different under soil 6 (Iwo soil series). Overall, capillary irrigation T1 and T4 performed better than others across all the soil types, although the 50.8 mm (T4) was better than 12.7 mm (T1) under soil 1 (fine sand). A similar trend was also observed in the second phase of the experiment (Figure 6b). The poor performance observed under sprinkler irrigation (watering can) system might be due to water losses through evapotranspiration. On the other hand, CISs (T4, T3, T2, and T1) possibly reduced water losses by supplying water to the topsoil from a buried reservoir only when required as maybe indicated by evaporative demand on capillary tubes. This means that the spread of the water in the topsoil depends on the capillarity, intermolecular attractions in soil and energy gradient as affected by soil physical and chemical properties.

These results indicate the effectiveness and reliability of the CIS since the supply of water was stopped for three weeks, and the performance was unaltered after the restart. The capillary irrigation methods supplied soil water close to the field capacity, similar to the performance observed in the first phase of the irrigation experiment (Figure 6b). Zotarelli et al. (2010) reported that monitoring soil water content and maintaining it close to the field capacity would minimise plant drought stress and increase plant readily available water essential for irrigation management.

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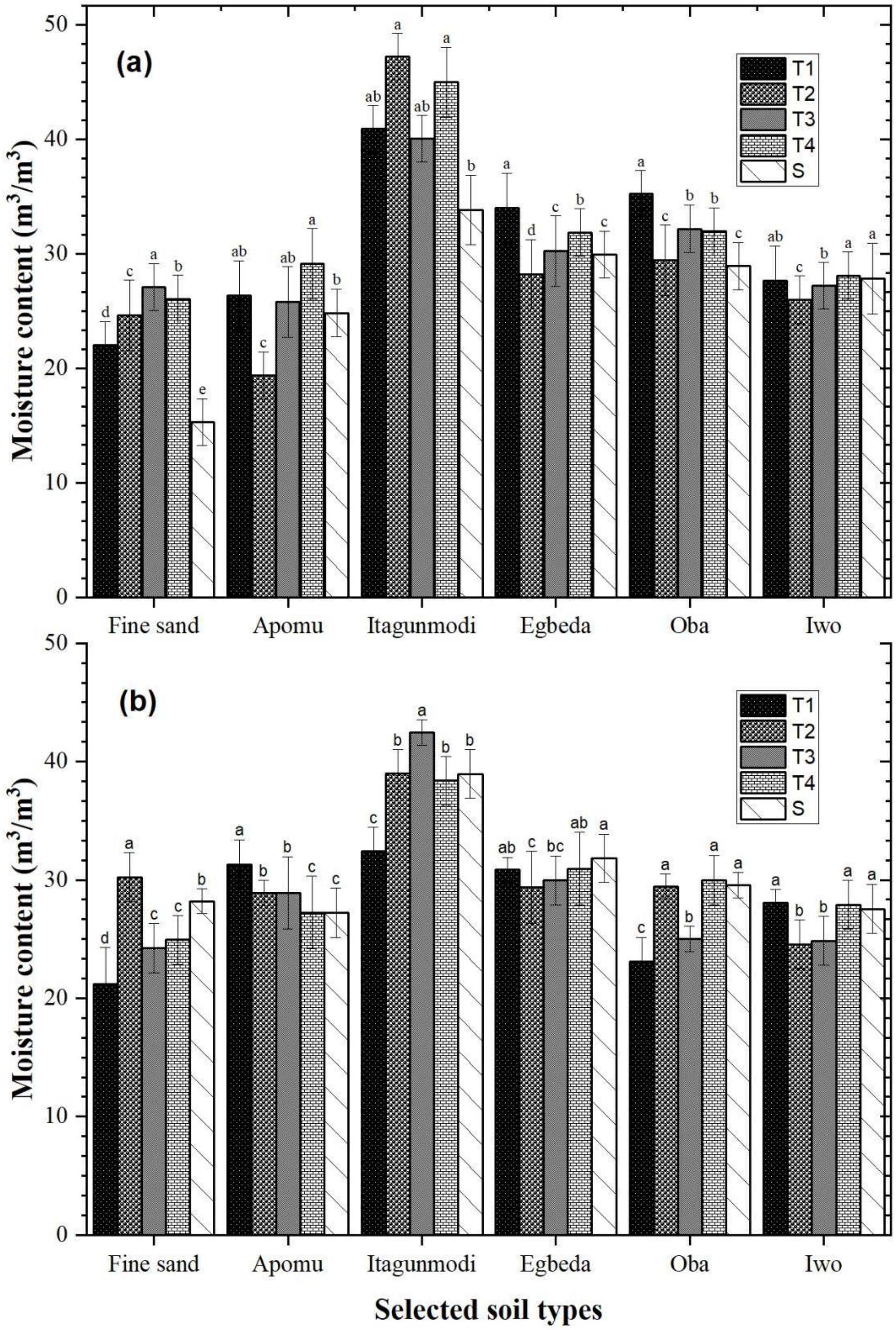


Figure 6. Performance of the capillary node sizes tested under the selected soil types during an extended first (a) and second phase (b) experiment. S=Sprinkler irrigation, T1= 12.7 mm; T2 = 19.1 mm; T3 = 25.4 mm; and T4 =

50.8 mm capillary node sizes. Small letters are statistical mean separations, means in the same soil type with the same alphabets are not significantly different at $p < 0.05$.

3.4 Performance of the capillary node sizes on the field

The performance of the CISs on the field (Figure 7) were similar to what was observed in the rectangular capillary irrigation containers (Figure 6). Each of the capillary node sizes performance on the field followed a similar trend as observed in the irrigation containers. The soil moisture distribution under capillary node size 50.8 mm diameter (T4) was significantly higher than other capillary node sizes, although it was not significantly different from 25.4 mm (T3) and 12.7 mm (T1). The 19.1 mm (T2), on the other hand, gave the lowest average moisture distribution, but it is not significantly different from 25.4 mm (T3) and 12.7 mm (T1) (Figure 6b). This underscores the capacity of the node sizes to distribute water by capillarity in response to the physical and chemical properties of the soil under study (Tables 1 and 2).

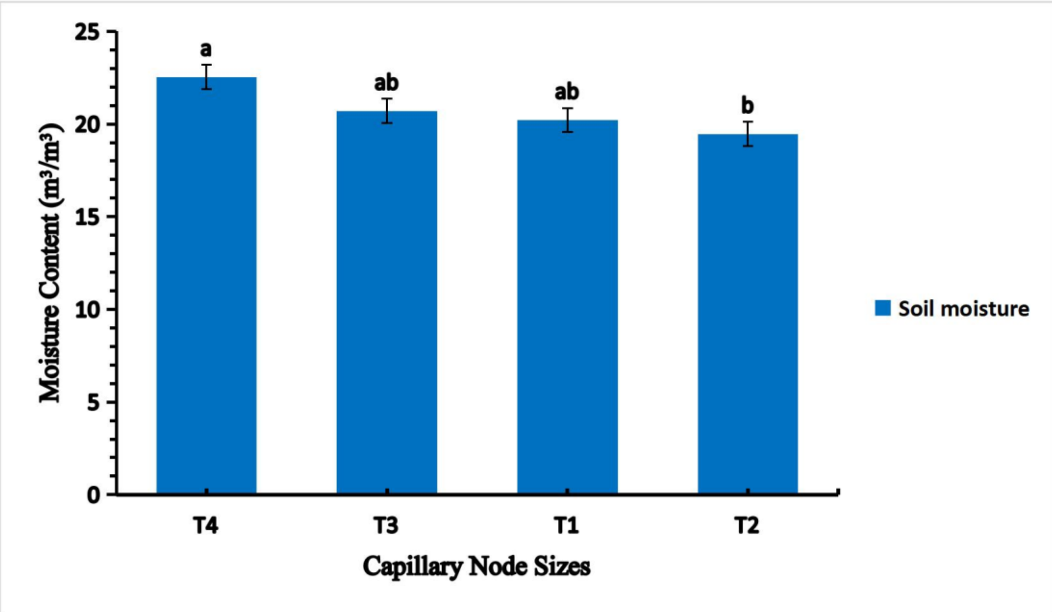


Figure 7. Performance of the capillary node sizes tested on the field across the selected soil types. S=Sprinkler irrigation, T1= 12.7 mm; T2 = 19.1 mm; T3 = 25.4 mm; and T4 = 50.8 mm capillary node sizes. Note: - Means with the same alphabets are not significantly different at 0.05 level of probability according to Duncan's Multiple Range Test.

3.5 Empirical modelling of the wetted radius under a point source CIS

The empirical model structure was described with a nonlinear form. The nonlinear expressions describing the horizontal spread of soil moisture from a point source under capillary irrigation might take the general forms of:

$$R = \Delta\theta^{\alpha} S^{\beta} \rho_b^{\lambda} K_{unsat}^{\delta} \qquad (3)$$

where R = surface wetted radius (cm); $\Delta\theta$ = average change of the water content within the wetted zone (%); K_{uns} (cm/hr) = unsaturated hydraulic conductivity; ρ_b = soil bulk density (g/cm^3); S = sorptivity (cm/s$^{1/2}$); and α, β, λ, and δ = best-fit empirical coefficients. A nonlinear regression approach was used in the Eviews (version 10) statistical package to find the best-fit parameters for equation (3).

The experimental data obtained (screenhouse) from the capillary irrigation experiment under different soil types as tested under different capillary node sizes were subjected to multiple regression analysis based on the identified model structure to generate the coefficients that characterise the empirical model (Equation 3). Nonlinear regression was used to find the best-fit empirical coefficients of the proposed model structure based on data collected from field experiments [12–14]. The equations generated for the surface soil wetted radius under each of the capillary node sizes (CISs) as tested under different soil types are as shown below;

Capillary Irrigation T1

$$R_{T_1} = \Delta\theta^{-0.7510} S^{0.2392} \rho_b^{3.2016} K_{unsat}^{-0.9853} \tag{4}$$

Capillary Irrigation T2

$$R_{T_2} = \Delta\theta^{-0.9213} S^{0.4341} \rho_b^{5.5144} K_{unsat}^{-0.7301} \tag{5}$$

Capillary Irrigation T3

$$R_{T_3} = \Delta\theta^{-1.0163} S^{-0.7076} \rho_b^{7.2278} K_{unsat}^{-0.6576} \tag{6}$$

Capillary Irrigation T4

$$R_{T_4} = \Delta\theta^{-1.0155} S^{-0.8156} \rho_b^{9.8350} K_{unsat}^{-0.5567} \tag{7}$$

Equations 4 to 7 may provide a simple description of the surface wetting pattern under CIS by estimating the soil surface wetted radius under a point source CIS. The nonlinear relationship of the soil wetted radius '**R**' with the average moisture content during the irrigation, Δ and unsaturated hydraulic conductivity, $_{na}$ emphasised the importance of these properties in predicting the spread of water under capillary irrigation in different soil types.

The quantitative inconsistencies observed in the r^2 values may be due to the inadequacy of the identified model structure. A similar result was reported by Lubana and Narda [64], who observed some variations in the predicted values compared to observed values, and they attributed these variations to the empirical nature of the developed equations. Similarly, Al-Ogaidi et al. [14] attributed the difference between model predicted values for soil wetting pattern and field measured values to differences in soil micro-aggregation and organic matter content.

3.6 Model evaluation

The distribution of the measured wetted radius vs the predicted wetted radius obtained using the empirical equation (Equation 4 to 7) developed for each capillary node size is presented in Figure 8 and 9. The moisture content of the wetted zone reduced with increasing wetted radius (Figure 8). The pattern indicates a declining wetting front, which suggests the limit of moisture transmittance capacity of the capillary nodes. Accordingly, to evaluate the performance of the model, the measured wetted radius across different soil types were plotted against the predicted wetted radius in scatter plots as shown in Figures 9 (a - d), and the regression parameters were obtained. The coefficient of determination (r^2), the slope, and the intercept of the regression line fitted to data are essential elements for evaluating model performance [65]. The regression line under capillary node size 12.7 mm diameter (T1) gave an r^2 of 57%, 19.1 mm diameter node size (T2) gave r^2 of 84%, while 25.4

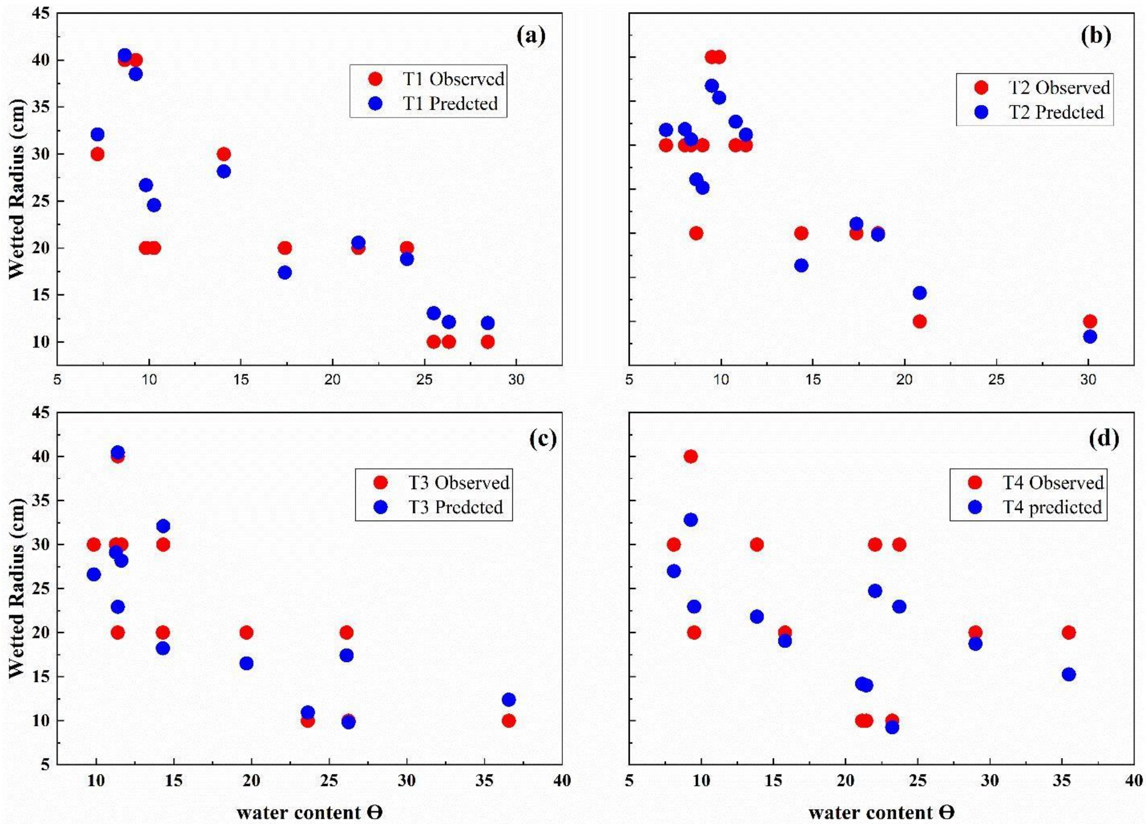
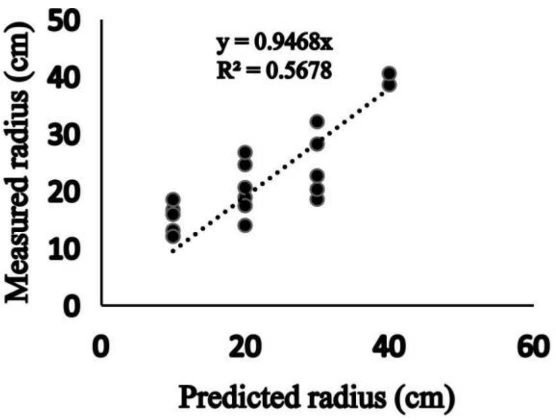
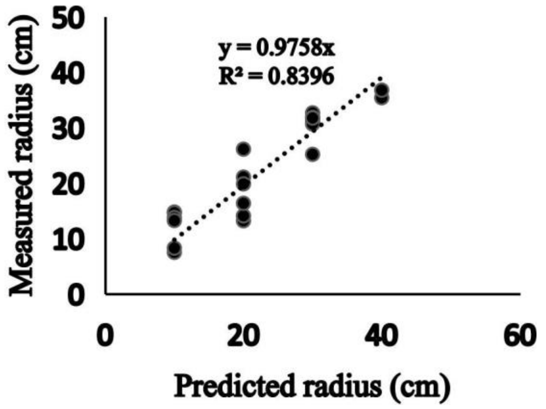


Figure 8. Soil water content at measured wetted radius and predicted wetted radius. Where capillary node size T1= 12.7 mm; T2 = 19.1 mm; T3 = 25.4 mm; and T4 = 50.8 mm.

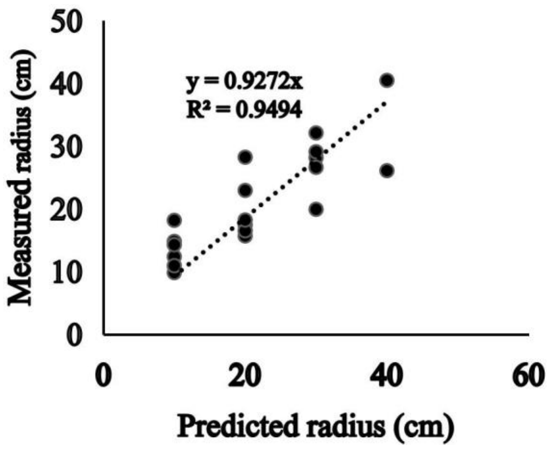
mm (T3) and 50.8 mm (T4) diameter node sizes gave an r^2 of 95% and 93%, respectively and their respective slope and the intercept values were consistent (Figure 8). This suggests that the empirical equation developed in this study (Equation 4 to 7) could explain 93%, 95%, 84%, and 57% of the measured wetted radius using capillary node size T4, T3, T2, and T1, respectively. The considerable high r^2 value of capillary node T4 models suggest it potential to predict the lateral spacing of 50.8 mm node size reasonably per unit land area for optimal water application and distribution for crop growth.



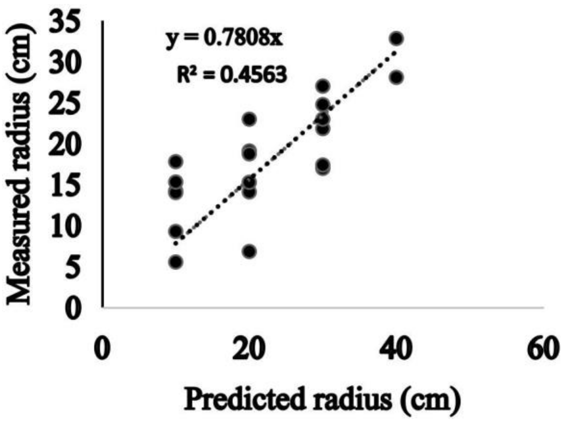
(a) 12.7 mm diameter node size (T1)



(b) 19.1 mm diameter node size (T2)



(c) 25.4 mm diameter node size (T3)



(d) 50.8 mm diameter node size (T4)

Figure 9. Regression of the measure wetted radius versus the model predicted radius across the studied soils.

4. Summary and conclusion

The study aimed to optimize the water distribution efficiency of CIS developed by Oyedele et al. [8] in relation to different soil textures. The water application and distribution uniformity of the point source capillary node sizes (12.7 mm, 19.1 mm, 25.4 mm, and 50.8 mm diameters) were investigated under different soil types at the Screenhouse and the Teaching and Research Farm at Obafemi Awolowo University, Ile-Ife, Nigeria.

The results showed that the soil wetted radius increased with increase in clay content of the soils, from sandy soils to sandy clay soils. Itagunmodi soil series had the highest amount of soil moisture spread at each of the designated points measured due to its moderately high contents of silt and clay (54%) fractions, while fine sand had the lowest moisture distribution due to its coarseness (96%). Soil moisture spread under Egbeda, Oba, and Iwo series were similar at each of the designated points of measurements due to the similarities in their silt and clay contents (26.93%, 29.60%, and 26.93%, respectively).

This study showed that soil water content distribution under CIS is a function of the capillary node size and soil physical properties like hydraulic conductivity, bulk density, texture, and soil sorptivity. This study also indicated that capillary node sizes 12.7 mm and 50.8 mm diameters were most appropriate for better soil moisture distribution under the six soil types. The empirical equations generated from this study can be used to predict the soil surface wetted radius (spacing) for 12.7 mm; 19.1 mm; 25.4 mm; and 50.8 mm diameter capillary node sizes under different soil types. This is important in designing a suitable and effective CIS for adequate row and lateral capillary node spacing to miximize irrigation efficiency. Thus, the installation spacing for different capillary node sizes can be inferred in multiple nodes outlet design. The findings from this study provided an essentail tools for designing a cost-effective and efficient CISs that can maximize crop yields and quality, and conserve water and nutrients for plant growth. Therefore, CIS is a promising solution to address irrigation and food security challenges, particularly in water-scarce regions. This results can be carefully extrapolated to all soil assoications in the southwestern Nigeria, however, further study should be conducted to cover more soil assoications in Nigeria.

Declarations

Author contribution statement

Gbadegesin, LA: Conceived and designed the experiments; Analyzed and interpreted the data; and Wrote the paper.

Durodoluwa JO and Fatai Oladapo Tijani FO: Conceived and designed the experiments; Supervised, Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Ibitoye RG: Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Available at https://doi.org/10.5281/zenodo.7738481

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Appendix A

Table A.1

Effects of soil types on soil water distribution (m^3/m^3) tested under the five irrigation methods

	Selected Soil Series					
Points	1	2	3	4	5	6
C	21.59b	26.41b	42.14a	30.97b	31.84b	26.41b
L1	20.75c	31.98ab	39.45a	31.56ab	31.44ab	26.42bc
L2	22.97d	24.14d	38.34a	32.31b	30.31bc	28.79c
R1	21.34f	24.83e	40.21a	31.29c	32.28b	27.25d
R2	24.72d	23.73e	39.24a	30.96b	31.39b	28.80c
UP1	22.35b	24.53b	41.42a	30.57b	31.46b	26.59b
UP2	19.81f	23.17e	38.37a	29.32c	31.26b	27.09d
Do1	21.39f	23.68e	40.08a	28.79c	30.12b	25.00d
Do2	20.42f	25.43e	40.13a	31.20c	32.22b	26.73d
EG1	23.75e	24.67d	39.47a	31.1b	31.11b	28.63c
EG2	26.29e	25.53f	39.39a	30.67c	31.63b	28.32d
EG3	27.45d	24.59e	40.19a	31.09c	33.35b	29.60c
EG4	26.22d	24.24e	39.55a	31.00b	31.53b	28.64c

1= fine sand, 2= Apomu, 3= Itagunmodi, 4= Egbeda, 5= Oba, and 6= Iwo series. C= Center of the *rectangular* container, L1 and L2 = 10 cm and 20 cm left of C, R1 and R2 = 10 cm and 20 cm right of C, Do1 and Do2 = 5 cm and 10 cm south of the breadth away from C while Up1 and Up2 = 5 cm and 10 cm north along the breadth, respectively. EG1, EG2, EG3 and EG4 = vertexes of the rectangular container. Means in the same row with the same alphabets are not significantly different at 0.05 level of probability according to Duncan's Multiple Range Test.

Table A.2

Effects of the irrigation methods on soil water distribution measured across the designated distances (points) on the selected soil types tested under the five irrigation methods.

	Irrigation methods performance (m^3/m^3)				
Points	S	T1	T2	T3	T4
C	30.23a	29.23a	39.39a	29.64a	30.07a
L1	27.91a	30.45a	28.10a	29.39a	35.67a
L2	25.76d	31.91a	29.16c	31.03b	31.21b
R1	26.94d	31.75a	28.68c	30.41b	30.03b
R2	25.76d	31.91a	29.16c	31.03b	31.21b
UP1	27.54a	30.62a	28.09a	30.08a	39.62a
UP2	24.65d	30.22a	27.63c	29.40ab	29.01b
Do1	28.12b	28.90a	26.95c	28.06b	29.06a
Do2	25.47d	31.40a	28.78c	30.51b	30.86ab
EG1	25.66d	31.51ab	28.78c	31.08b	31.95a
EG2	26.58d	31.85ab	29.39c	31.55b	32.27a
EG3	26.96c	32.27a	30.50b	32.66a	32.94a
EG4	25.00c	32.39a	29.24b	32.17a	32.24a

S=Sprinkler irrigation, T1= 12.7 mm, T2 = 19.1 mm, T3 = 25. 4 mm, and T4 = 50.8 mm diameter node capillary irrigation. C= Center of the rectangular container, L1 and L2 = 10 cm and 20 cm left of C, R1 and R2 = 10 cm and 20cm right of C, Do1 and Do2 = 5 cm and 10 cm down of C, Up1 and Up2 = 5 cm and 10 cm away from C along the breadth respectively. EG1, EG2, EG3 and EG4 = vertexes of the rectangular container. Note: - Means in the same row with the same alphabets are not significantly different at 0.05 level of probability according to Duncan's Multiple Range Test.

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