Potential of low-cost subsurface irrigation system in maize (*Zea mays* L.) production in high water scarcity regions

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Abstract: Improvement of agricultural practices under limited water availability is a key solution for arid and semi-arid areas food shortage problems. Pressurized irrigation technologies have made great improvements in the field water use efficiencies; however, the construction cost of these systems was usually beyond the dry land small-farmer means. Low-cost porous material was used for maize water supply under a typical dry environment. Field experiments were conducted to evaluate the influence of subsurface irrigation systems made of locally produced clay pots and clay pipes on the growth, yield and water use efficiency of maize (*Zea mays* L.) in the dry land of Sudan. Clay pots release point source water to the surrounding soil as emitters, whereas clay pipes are envisaged as subsurface buried porous tubing. The maize yield obtained from plots having subsurface clay pipes irrigation system was higher (30%) than the maize grown under the surface irrigation system. The experiments proved that the clay pipe and pitcher irrigation method is water-saving technology, which optimizes yields per unit of water used when compared to the surface irrigation method. Also, the clay pipes and pitchers are conservation irrigation systems, which save about 96.58% and 95.46% of the water used for irrigation, respectively, when compared to the surface irrigation system.

Keywords: pitcher, pipe, water use efficiency, drylands

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1 Introduction

Subsurface drip irrigation (SDI) is a low-pressure, high-efficiency irrigation system that uses buried drip tubes or drip tape to meet crop water demands. It provides water directly to the root zone, thus maximizing water utilization and minimizing moisture loss to evaporation, deep percolation and surface runoff (Reich et al., 2014). Reducing or eliminating high soil-water evaporation, deep water percolation beyond the root zone, and overland flow

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will improve water use efficiency at the field scale. Besides increasing water use efficiency, there are several environmental protection benefits due to reducing nutrients flow to the surface and subsurface aquatic ecosystem. At the agricultural field scale, eliminating water losses by deep percolation and runoff will enhance the use efficacy of fertilizer and agricultural chemicals. Under surface irrigation systems, farmers wet vast areas to irrigate small cropping areas, which lead to water loss due to evaporation. The evaporation problem is highly prominent under arid and semi-arid environments. Thus, the utilization of trickle irrigation techniques will conserve water by reducing the wetted area and deep percolation. Additionally, trickle irrigation will reduce weed infestation problems (Megersa and Abdulahi, 2015). Thus, trickle irrigation will reduce water, energy and agricultural chemical costs (Rodríguez-Sinobas and Gil-Rodríguez, 2012).

However, the technology and materials of traditional SDI are not always available to farmers in developing countries, making it an uncommon practice in those low-income regions. Therefore, farmers seek to apply locally available methods to meet crop water demands; one of these methods is pitcher irrigation.

Pitcher irrigation is an ancient watering method that has been practiced in various forms in Iran, India and some African countries (Mondal, 1974; Bainbridge et al., 1998; Bainbridge, 2001; Siyal et al., 2009; Ashrafi et al., 2002; and Qiaosheng et al., 2007). It has been used to irrigate various annual and perennial plants on small scale farming in arid and semi-arid regions (Mondal, 1974; Anonymous, 1997; Bainbridge, 2001; Vasudevan et al., 2007; and Abu-Zreig et al., 2018). The pitcher-irrigation technique uses clay pots or clay pipes baked at high temperatures to produce walls of the desired porosity. Pitchers or clay pipes are buried in the soil and filled with water at various time intervals to keep moisture levels favorable to plant growth (Gischler and Jauregui, 1984). Water gradually seeps out into the soil due to the pressure gradient across the wall of the pitcher resulting from the hydraulic head inside the pitcher and the soil suction head on the outer surface. Daka (1991) found that using clay pots resulted in a 70% water saving compared to watering with buckets and sprinkler irrigation under maize and cauliflower crops. The technique is simple, cheap, have large water-saving potential and has auto-regulative capabilities (Bainbridge, 2001; Mondal, 1978; Batchelor et al., 1996; Daka, 2001; Vasudevanet al., 2011; and Abu-Zreig et al., 2006).

Porous clay pipes buried in the soil is an improved version of the traditional pitcher irrigation in which both conveyance and seepage of the water are done instantaneously by the same pipe. Clay pipes are porous, and when buried into the soil and filled with water, it oozes out water through their micro-pores and wets the surrounding soil similar to modern porous tubing SDI systems. Subsurface clay pipes save water and improve yields by eliminating surface water evaporation and reducing the incidence of weeds and disease. However, field experimental reports on the use of subsurface clay pipes for crop production seems to be scarce in the literature (Ashrafi et al., 2002).

The effect of buried clay pipes and pitchers on crop growth is somewhat scarce and conflicting. An early work carried by Batchelor et al. (1996) showed that subsurface buried pipes and pitchers increased the yield and water use efficiency of maize by an average of 64%. However, Agodzo et al. (1997) found that the crop yield of okra with pitcher irrigation was 35% less than that compared to drip irrigation. Ansari et al. (2015) found that pitcher irrigation increased the growth of some locally common species in urban landscapes (not significant at $p < 0.05$) compared to that of surface and drip irrigation but decreased water consumption by 60% and 30%, respectively. Therefore, a systematic experiment is needed to confirm the advantages of buried clay pipes and pitcher irrigation on crop growth in drylands.

In Sudan, maize is the fourth cereal crop in terms of cultivated area and production after sorghum, millet and wheat (Yassin, 2016). It is grown in both rain-fed and irrigated areas (Ahmed et al., 2008). This study was carried out in the Wadi El Rawakeeb area, Sudan where large areas are grown with maize and sorghum. The area has been extensively cultivated resulted in severe land degradation complemented by drought periods, (i.e, 1983-1984). Currently, residents of the Wadi (seasonal watercourse) face sand encroachment, erratic and low rainfall, high cost of groundwater exploitation, poverty, the prevalence of malnutrition among children (2-5 years). These problems are often attributed, among other factors, to inadequate food intake (Ahmed et al., 2011) due to decreasing land productivity. Therefore, there is a great need for efficient, low cost and suitable irrigation methods with high water saving potential to increase crop production, improve food intake and alleviate the income of small farmers. Pitcher and buried clay pipes irrigation technology is one of these promising traditional and potential methods that had not been yet applied in Sudan. Hence, the objective of this study was to evaluate the performance of the subsurface clay pipe and pot irrigation system for maize (*Zea mays* L.) production and water use efficiency in the arid region of Sudan.

2 Materials and methods

2.1 Study site

Field experiments were conducted in the winter season (2016/2017) at El Rawakeeb Desertification Research Station Farm (Sudan) with Latitudes 15^o 27' and 15^o 30 ' N, Longitudes 32^o 13 $^'$ and 32^o 16 $^'$ E and altitude 420 m above sea level, as shown in Figure 1.

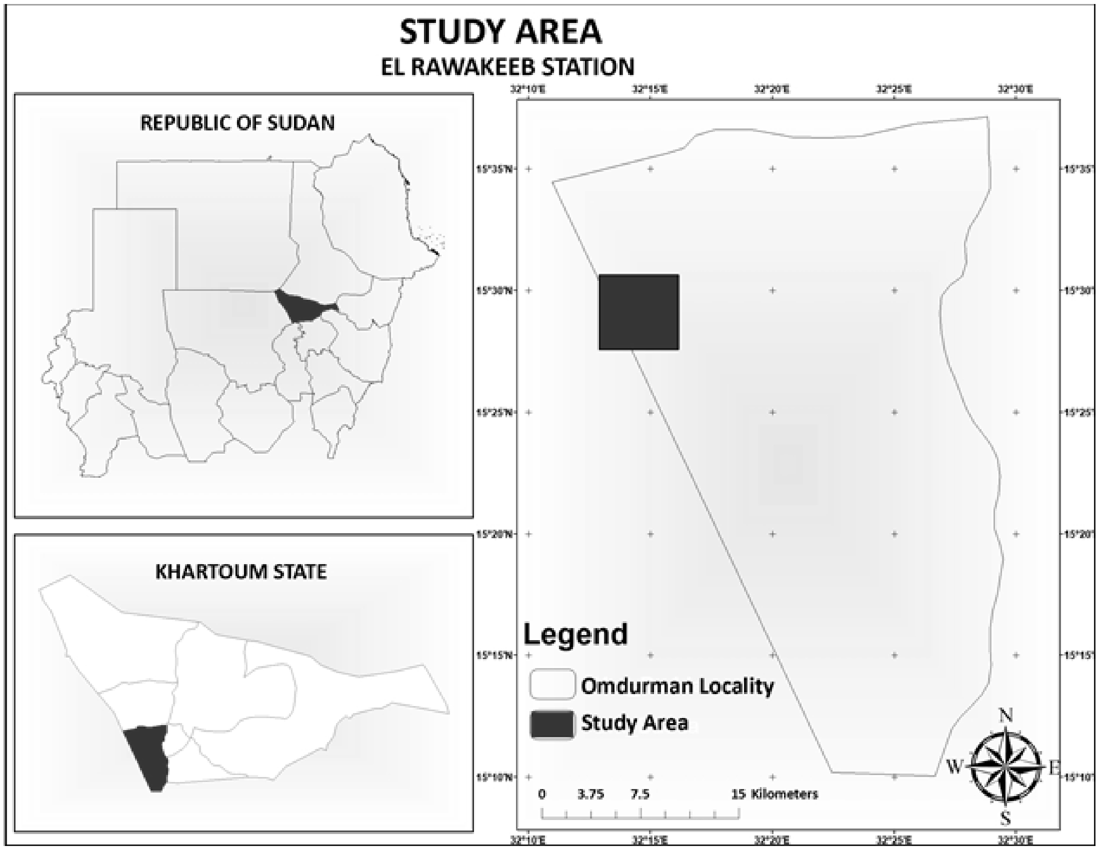

Figure 1 The location of the study area in central Sudan

The soil of the farm was sandy clay loam (50% sand, 21% silt and 29% clay), 7.7 pH (paste), 0.094% organic carbon, 0.011% total nitrogen, 0.53 dSm^{-1} electrical conductivity, and classified as Aridisol. (Abdellatif and Elhag, 2015).

The climate of the area is semi-desert, characterized by erratic and low annual rainfall with an annual average of 163 mm, falling primarily in July and August (Figure 2). The mean daily maximum and minimum temperatures are 37°C and 21.6°C, respectively (Figure 3).

The minimum, average and maximum temperature during the study period between October 2016 and February 2017, was 14ºC, 27.6ºC and 40.7ºC, respectively. On the other hand, the minimum, average, maximum relative humidity, and rainfall during the same period was 10%, 53%, 28.2%, and 0 mm, respectively.

2.2 Experimental setup and water use monitoring

Nine experimental plots of 4×6 m^2 area were prepared in the field and marked by 20 cm height earthen border separate by 1-m wide path. Three plots were used to install subsurface clay pipes at a spacing of 1-m, and three plots were used to install six pitchers buried to their neck placed in the middle of the plots, as shown in Figure 4. The other three plots were used for surface irrigation as control.

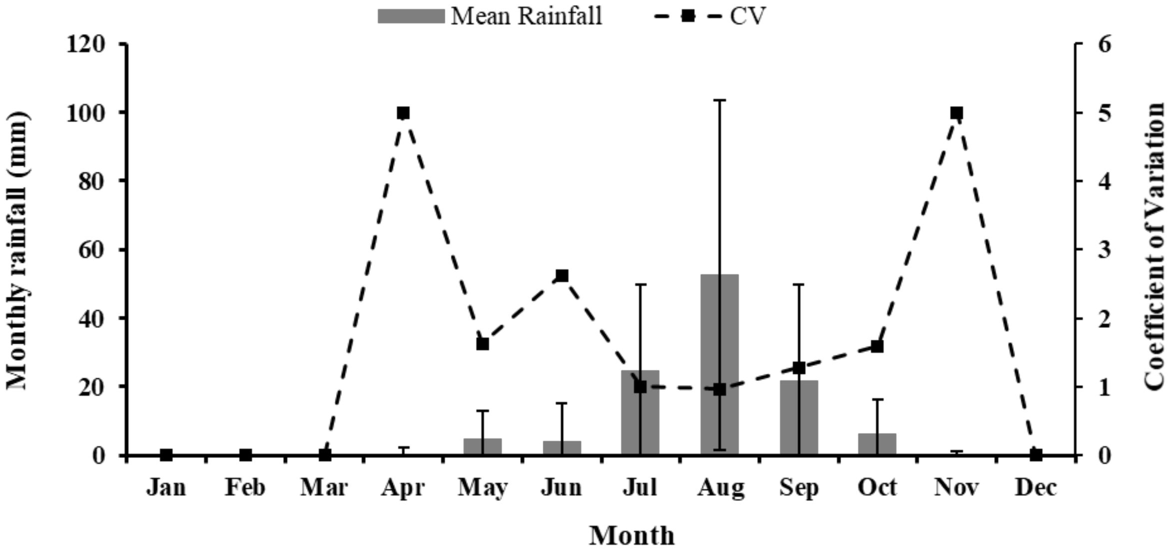

Figure 2 Long-term monthly average rainfall and coefficient of variation for Khartoum Station. located 20 km far from the experimental site (January 1980 – April 2017)

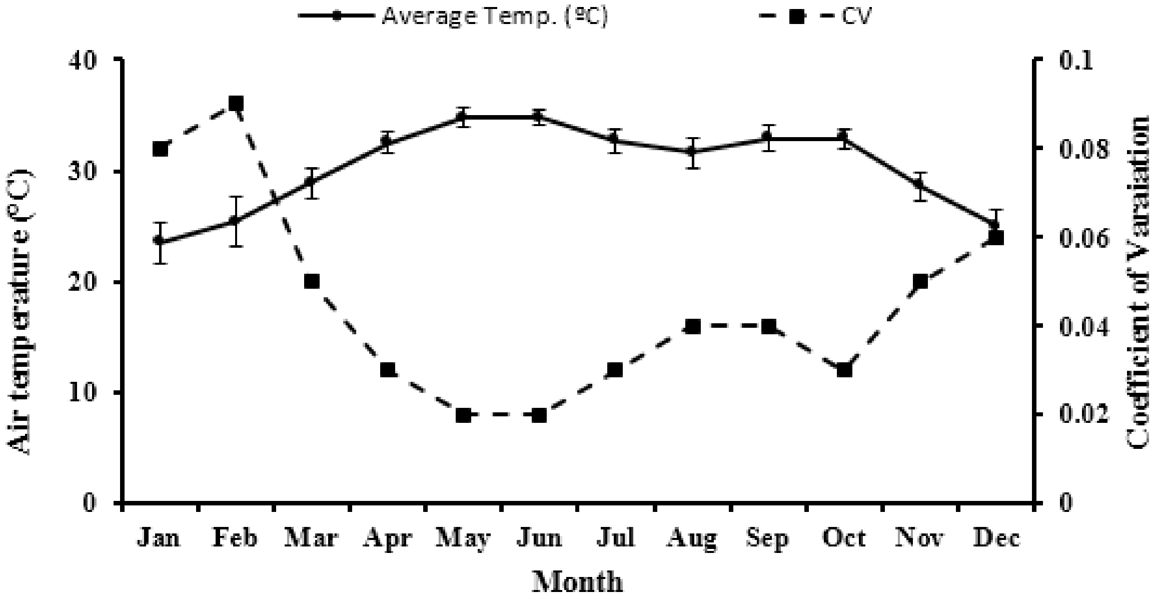

Figure 3 Long-term monthly average temperature and coefficient of variation for Khartoum Station (January 1980 – April 2017)

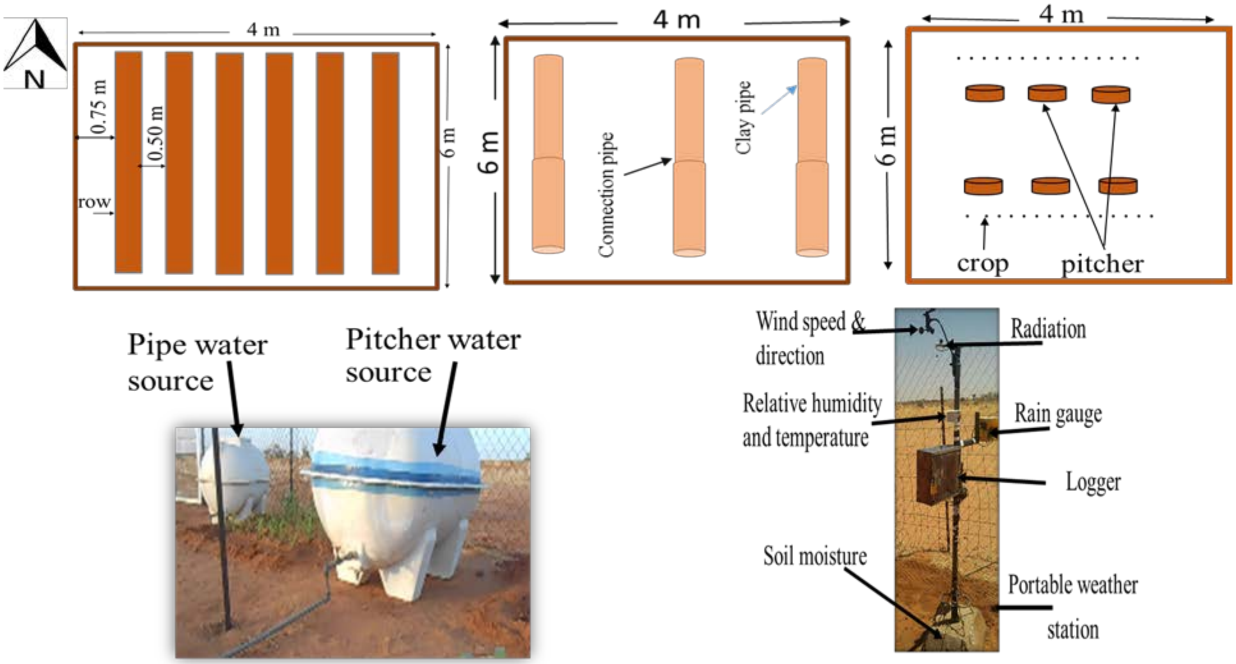

Figure 4 Schematic diagram of the experimental layout in the field

The subsurface irrigation systems were designed using locally made clay pots and pipes obtained from a local producer. The pitchers used in the study have a mean capacity of 4.42 L each, a mean surface area of 1104.70 cm^2, a mean height equal to 41.73 cm, maximum outside diameter was 12 cm and a wall thickness was 1.33 cm. The seedbeds were prepared in the experimental plots, and pitchers were buried in the center of the plots, area (6×4 m^2), up to their neck at a spacing of 2×2 m^2. The clay pipes were prepared using segments of 50 cm long pipes cemented together and to form 1 m long porous pipes. The volume of 2 m long pipe was 3.02l, a surface area equal to 3306 cm^2, maximum outside diameter was 12.08 cm, and wall thickness was 1.33 cm. In each experimental plot of 4x6 m^2 in area, three pipes were buried in parallel at 2 m spacing at a depth of 30 cm below the soil surface. Irrigation water was fed to the buried clay pipes and pitchers from an overhead two tanks via two separate lines.

The three irrigation systems were arranged in a Randomized Completed Block Design with three replications and planted with maize (*Zea mays* L.). Seeds of local maize variety (Hudieba-2) were sown on the 26th of October 2016 at a spacing of 20 cm from the pitcher's mouth and 20 cm from both sides of the pipes and 20 cm between the plants. For the control plot, maize seeds were sown at 20×20 cm spacing. Nitrogen fertilizer (urea) was applied at a rate of 43 kg N ha^{-1} after 4 weeks of sowing to the three systems of irrigation.

Growth parameters were measured at 30, 45 and 75 days after sowing. At the end of the experiments, the yield and yield components (cob length, cob diameter, cob weight, weight of seed/plant, weight of 100 seeds, number of seed /cob, weight of fresh and dry biomass and grain yield as ton ha^{-1}) were recorded and water use efficiencies (WUE, kg mm $^{-1}$) can be expressed as yield per unit water used, as shown in Equation 1.

$$WUE = \frac{yield}{plant\ water\ used} \tag{1}$$

Soil water content in the experimental plots at various depths was monitored using moisture sensors EC5, 5TE and 5TM from Decagon Devices (USA), and data loggers, EM50, daily. Moisture sensors were inserted at three depths (30, 50 and 70 cm), below the soil surface. Data loggers were monitored on a regular basis to check the working conditions of moisture sensors and correct any malfunctions of sensors. Data were downloaded from the data loggers using a computer with ECH2O utility software.

2.3 Statistical analysis

The obtained data were statistically analyzed according to the randomized complete block design (RCBD) using the Genstat® Discovery Edition 4 program. Differences among averages were tested using Duncan multiple range test at a 5% probability level.

3 Results and Discussion

3.1 Crop growth parameters

The growth parameters of maize including plant height, number of leaves, stem diameter and area of leaves are summarized in Table 1, whereas maize yield and yield characteristics are shown in Table 2. The growth parameters of maize under subsurface clay pitchers and subsurface clay pipes (Table 1) were higher than that for surface irrigation, although not significantly different ($p > 0.05$). However, the analysis of variance revealed that the maize yield and yield characteristics were significantly higher ($p < 0.05$) in the case of clay pitcher's ad clay pipes compared to surface irrigation (Table 2).

Table 1 Means of vegetative growth parameters of maize (*Zea mays* L.) under different irrigation systems

Irrigation System	Plant age (days)											
	Plant height (cm)			Number of Leaves			Stem diameter (cm)			Leaf area (cm^2 plant^{-1})		
	30	45	75	30	45	75	30	45	75	30	45	75
Pipe	31.4 a	84.9 a	94.1 a	7.0 a	8.57 ab	11.27 a	0.55 a	1.14 b	1.48 b	259 a	379 a	595 a
Pitcher	30 a	74.8 ab	102.4 a	6.93 a	9.17 a	11.93 a	0.70 a	1.64 a	1.73 a	239 a	292 b	575 a
Surface	24.7 a	57.3 b	72.6 a	6.6 a	7.23 b	10.8 a	0.40 a	1.25 b	1.35 b	267 a	392 a	405 b
Means	28.7	72.33	89.6	6.84	14.99	11.33	0.55	1.34	1.52	255	354.33	525
SE	3.59	10.63	17.49	0.78	0.67	0.85	0.09	0.095	0.11	78.2	30.6	69.4
CV	12.5%	14.7%	19.5%	11.4%	8.1%	7.5%	16.1%	6.0%	7.0%	15%	12%	19.3%

Note: SE is the standard error, and CV is the coefficient of variation. For a given parameter and day after sowing (30, 45 and 75 days), the same letter shows no significant differences between irrigation systems.

The highest yield of maize (5.37 ton ha^{-1}) was observed for the pipe irrigation system and it was 11% significantly ($p \leq 0.05$) higher compared to the pitchers' method and also higher ($p \leq 0.001$) by 30% compared to the surface irrigation method. The yields under clay pitcher and pipes were higher than the average yield recorded under a similar environment using surface irrigation in Sudan, which was 2.95 ton ha^{-1} (Abdel-Rahman et al., 2001). The cob length, weight and number of seed, the weight of 100 seeds and weight of seeds per plant were significantly ($p < 0.05$) higher in subsurface pipe irrigation compared to surface irrigation system. In general, clay pipe irrigation was performing better than that of clay pot irrigation system, however, the difference was not significant ($p \leq 0.05$). On the other hand, the difference in fresh biomass at the pipe method (1438 g) was significantly higher than the pitcher method (1283 g), as shown in Table 2.

Table 2 Means of yield and yield components of maize (*Zea mays* L.) as affected by irrigation systems

Irrigation System	Cob length (cm)	Cob diameter (cm)	Cob weight (g)	Weight of seed/Plant(g)	Weight of 100 seed (g)	Number of seed / Cob	Weight of fresh biomass (g)	Weight of dry biomass (g)	Grain yield (ton ha^{-1})
Pipe	15.65 a	4.43 a	170.4 a	355.6 a	16.07 a	337.4 a	1483.0 a	967.0 a	5.37 a
Pitcher	15.75 a	4.31 a	152.0 a	338.7 ab	15.61 a	323.8 a	1283.0 b	867.0 ab	4.83 a b
Surface	13.98 b	3.82 b	104.6 b	302.9 b	14.67 b	299.3 b	967.0 c	760.0 b	4.12 b
Means	15.12	4.18	142	332.4	15.45	296.7	1244	864.67	4.77
SE±	0.34	0.17	19.62	20.32	0.400	8.34	48.6	50.9	0.37
CV	2.3%	4.1%	13.8%	6.1%	2.6%	2.6%	3.9%	5.9%	7.7%

Note: SE is the standard error, and CV is the coefficient of variation. For a given parameter, the same letter shows no significant differences between irrigation systems.

The soil moisture content of the experimental plots under the subsurface irrigation systems, shown in Figures 5 and 6, revealed that the highest soil moisture content under the pipe irrigation system was found at 50 cm depth, followed by 70 cm and then 30 cm (Figure 5). While the highest soil moisture content under the pitcher irrigation system was found at 30 cm, followed by 50 cm and then 70 cm depths (Figure 6). Moreover, the highest soil moisture content under surface irrigation system was found at 50 cm, followed by 70 cm and then 30 cm depths (Figure 7).

3.2 Soil moisture trends

Therefore, the soil wetted zone under pitcher irrigation was kept near the soil surface compared to the pipe irrigation system, indicating higher losses due to evaporation. The moisture content in the control plots at the soil surface was constantly near saturation (30%) following flooding and reduced to field capacity (approximately 24% which obtained 24 h after irrigation).

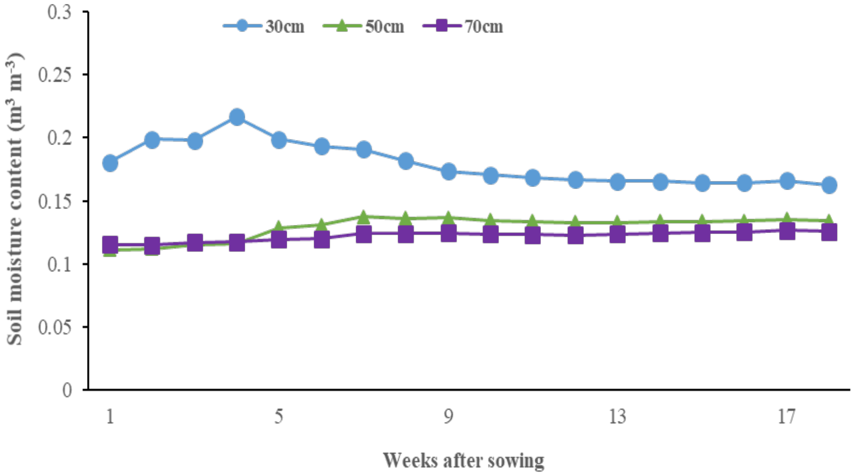

Figure 5 Volumetric water content (VWC) time series measured at different depths (30, 50 and 70 cm) under clay pitcher subsurface irrigation system

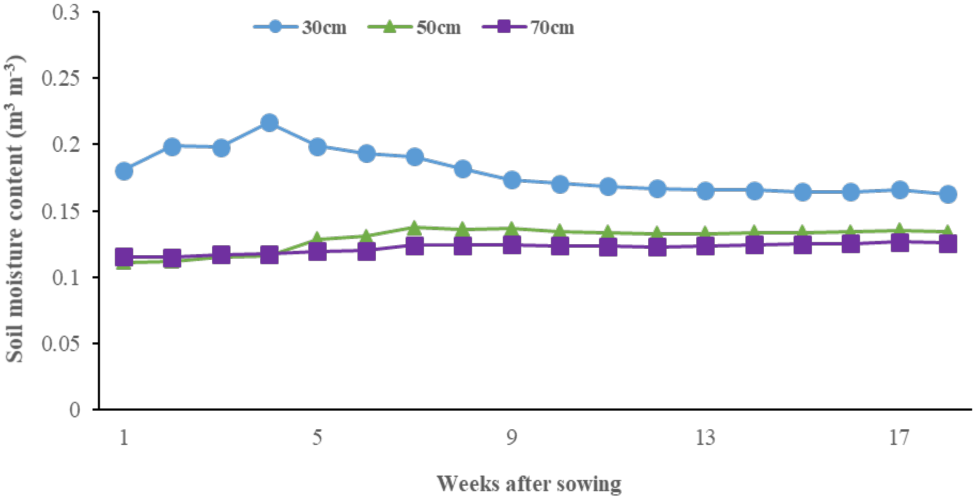

Figure 6 Volumetric water content (VWC) time series measured at different depths (30, 50, and 70 cm) under clay pipes subsurface irrigation system

3.3 Crop water use

The experimental results revealed that the influence of subsurface clay pipe and clay pot irrigation methods on water consumption and water use efficiency was great. The water consumption by maize under clay pipe irrigation was 165.28 m^3 ha^{-1}, 219.55 m^3 ha^{-1} for clay pot irrigation, and 4835.6 m^3 ha^{-1} for surface irrigation systems. This represents a decrease of 93% and 91% folds for clay pipes and pots, respectively, compared to the surface irrigation (Table 3).

This finding was in agreement with other researchers who found pitcher irrigation has high water-saving potential. Okalebo et al. (1995) reported that the clay pot irrigation technology is a conservation irrigation system, which saves between 50% and 70% of water, and Batchelor et al. (1996) found that the pitcher irrigation can hold water up to 70% when both compared to the conventional techniques of irrigation. Approximately 70%–80% of water saving compared to watering with can or bucket was recorded by Daka (1991) and Balakumaran et al. (1982), while Kefa et al. (2013) found that clay pots were more efficient than the furrow irrigation method by saving 97.1% of applied water for maize crop.

Table 3 Water consumption and water use efficiency of maize production under different irrigation methods

Irrigation system	Water use efficiency		
	$m^3 ha^{-1}$	$m^3 ton^{-1}$	$kg\ mm^{-1}$
Clay pipe	165.28	30.78	324.86
Clay pot	219.55	45.46	219.94
Surface	4835.56	1173.68	8.52
Means	1740.13	416.64	184.44

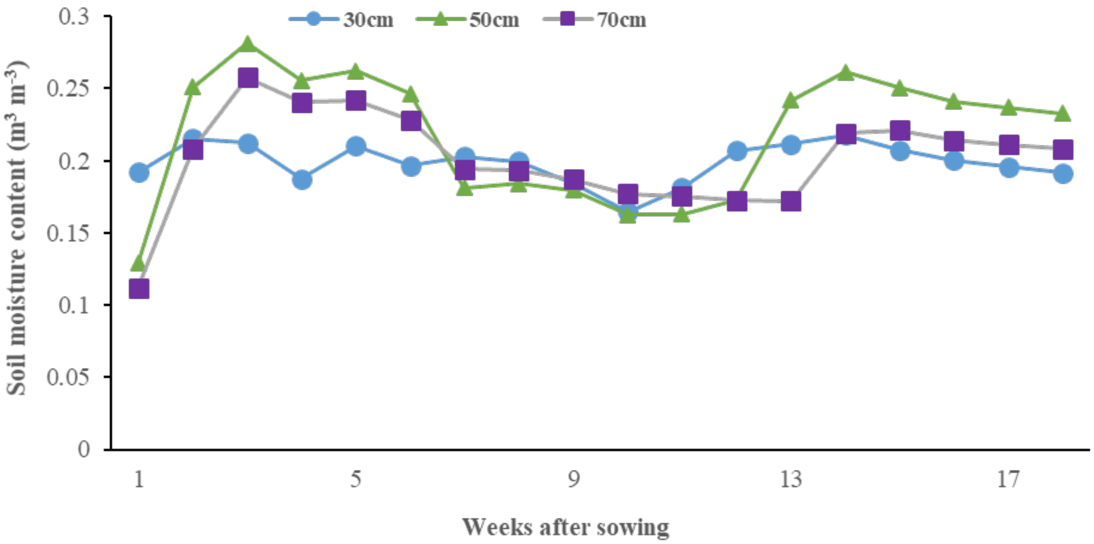

Figure 7 Volumetric water content (VWC) time series measured at different depths (30, 50, 70 cm) under surface irrigation system

This can be attributed to the decrease in water losses due to reduction of deep percolation, evaporation and reduction of weed infestation under clay pot irrigation compared to surface irrigation. In agreement with our study, Batchelor et al. (1996) found that water consumption by clay pitcher was more than clay pipes because the wetted zone in the case of pitchers remained close to the soil surface as shown in Figures 4 and 5. Therefore, soil water evaporation is expected to be larger in the case of pitchers compared to subsurface pipes. In addition, water losses also occurred during the filling of pitchers when they are empty. The water use efficiencies for the different treatments are shown in Table 3. These results revealed that subsurface clay pipes and pots have great water use efficiency. Maize grown under the clay pipe irrigation has higher water use efficiencies (324.86 $kg\ mm^{-1}$) followed by clay pot (219.94 $kg\ mm^{-1}$) and then surface irrigation (8.52 $kg\ mm^{-1}$). This is a 3700% decrease or 3700% increase in water use efficiency when expressed in $m^3\ ton^{-1}$ or $kg\ mm^{-1}$, respectively, for the clay pipes compared to the surface irrigation. The corresponding increase in the case of clay pots compared to surface irrigation was 2100%. A similar increase in water use was reported by Daka (2001) under the clay pots irrigation method compare to a conventional surface irrigation system which was more than 400%. Batchelor et al. (1996) pointed out that, the effectiveness of the subsurface clay pipe method in improving yields, crop quality and water use efficiency as well as being cheap, simple and easy to use in comparison with flood irrigation.

4 Conclusions

Experiments on the growth and yield of maize under surface, and subsurface irrigation using clay pipes and pitcher methods under arid environment we carried out. The results have shown that the subsurface clay pipe and pitcher irrigation systems were more efficient than the surface irrigation system, with water use efficiency to 2800% and 2100% decrease, respectively. The maize crop grain yields under the clay pipe and pitcher systems were higher than that under the surface system by 30% and 17%, respectively. Therefore, for efficient water management under arid areas using these subsurface irrigation techniques can offer a solution to water scarcity and would help in the conservation of water and utilization of more areas for agriculture.

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