PITCHER IRRIGATION: EFFECT OF PITCHER WALL PROPERTIES ON THE SIZE OF SOIL WETTING FRONT

Altaf Ali Siyal*, Abdul Ghafoor Siyal, Pirah Siyal***, Mujeeduddin Solangi**** and Imran Khatri******

*U.S.-Pak Center for Advanced Studies in Water, Mehran University of Engineering and Technology, Jamshoro.

**Department of Land and Water Management, Sindh Agriculture University, Tandojam.

***Allama I.I. Kazi Institute of Chemistry, University of Sindh, Jamshoro.

**** Department of Horticulture, Sindh Agriculture University, Tandojam.

.Corresponding Author: Prof. Dr. Altaf Ali Siyal, Email: siyal@yahoo.com

ABSTRACT: *Water use, efficient, simple, technically feasible, and economically viable irrigation methods for arid and water scarce areas of world are always emphasized. Clay pitcher irrigation is one of the water use efficiency, technically simple, economically viable and indigenous method of small scale irrigation for arid areas of the world. Success of the method depends entirely upon the seepage rate from pitcher wall, hence parameters which affect the water seepage were quantified in the present study. Six pitchers with non-significant difference in size, wall thickness, height and physical appearance were purchased and were branded as category A. Six more pitchers of similar size and height to those of in category A, but significantly different in wall thickness and other wall properties were also purchased and categorized as B. The experimental results revealed that the saturated hydraulic conductivity (K_s), wall thickness and porosity for pitchers in category A were 0.11±0.01 cm day^{-1}, 1.26±0.02 cm and 0.37±0.01 respectively, whereas they were 0.059±0.01 cm day^{-1}, 1.98±0.06 cm, and 0.31±0.01 respectively for pitchers in category B. The size of soil wetting front, after 5 days to initiation of seepage, was 22% more for pitchers in category A than to those in category B though both categories had pitchers of same size. This suggests that before field installation of pitchers, the radius of soil wetting front and seepage rate should be determined as it will help in deciding placement distance between the pitchers so that wet areas do not overlap each other.*

Keywords: hydraulic conductivity, seepage, water conservation, wetting front

INTRODUCTION

Although today irrigation covers only about 20 percent of the world's cultivated land, but irrigated land contributes 40 percent of the total food production [1]. So far global food production has kept pace with population growth; yet nearly 800 million people still remain malnourished. Tremendous increase in population in coming years shall need more food and fiber, which potentially will come through bringing more area under cultivation or by growing high yield crops. Bringing new areas under cultivation will result in increased demand for extra water for irrigation, particularly in the arid and semiarid regions of the world. It is judicious to conserve and use water efficiently for maximizing crop production per unit volume of the water application [2]. High-Tech irrigation methods no doubt save large quantities of water, but technical, economical and socio-cultural factors obstruct the adoption of these methods. Hence, developing and introducing simple, efficient, low input, easy to install, operate and maintain irrigation technologies, especially suitable for small scale irrigation in arid regions is one of the major tasks for the scientists [3, 4].

Pitcher irrigation method is one of these efficient methods which is used for small-scale irrigation where water is scarce, fields cannot be easily leveled, soils are coarse textured with high water infiltration rates, water is saline and cannot be normally used in surface irrigation methods [5], and in remote areas where fresh vegetables are expensive to fetch [6].

The size of the soil wetting front around pitcher affects the availability of soil water for plant growth. The number of plants around pitcher and their distance from pitcher wall depend on the size of wetting front. Soil wetting front is usually defined as the soil profile/area with a matric potential of -200 and -763 cm for the fine sand and sandy loam soils respectively [7]. It is reported that the water seepage from pitcher wall is affected by many factors such as the saturated hydraulic conductivity of the pitcher material [8, 9, 10], wall thickness, surface area [11], type of soil, type of crop and the rate of evapotranspiration. Effect of pitcher wall properties such as size of wall thickness, porosity and hydraulic conductivity on seepage rate is limited. The success and sustainability of a pitcher irrigation system depends on factors affecting water conductance from pitcher wall which need to be thoroughly studied. Keeping in view the importance of seepage rate of pitcher for sustainability of pitcher irrigation, present study was conducted to determine the effect of wall thickness, porosity and saturated hydraulic conductivity of pitcher on the size of the soil wetting zone.

MATERIALS AND METHODS

The study was conducted in the laboratory as well as in the laboratory as well as experimental field of Department of Land and Water Management, Sindh Agriculture University Tandojam, Pakistan. Six pitchers of the same size, wall thickness, color and physical appearance (category *A*) were selected and purchased from the local potter shop. Six more pitchers of size to that of category *A* pitchers, but of different wall thickness and physical appearance (category *B*) were also purchased. Those were brought to the laboratory for determining different physical parameters of pitchers as:

Thickness of pitcher wall

The thickness of the pitcher wall (L) was determined by breaking up pitchers at the end of the experiment and then measuring the thickness of the fractured pieces of pitcher wall with the help of Vernier Calliper.

Surface area of pitcher

The surface area of a pitcher was calculated by plotting its actual surface curve as a function of its height, as shown in Figure 1. Lines were first drawn with the help of chalk around the pitcher curvature at different locations along height of the pitcher. The circumferences at these positions were measured using thread. From these circumferences external diameters of the pitcher at various incremental points were determined. For each incremental height radius of a pitcher was measured. The surface area of each increment and then whole pitcher was calculated by using equations 1 and 2.

$$a_i = 2\pi x_i (y_i - y_{i-1}) \quad (1)$$

$$A = \sum_{i=1}^{n} a_i \quad (2)$$

where, a_i is incremental surface area, A is surface area of whole pitcher, x_i is external radius of i[th] segment and y_i is the height of i[th] segment above base of the pitcher.

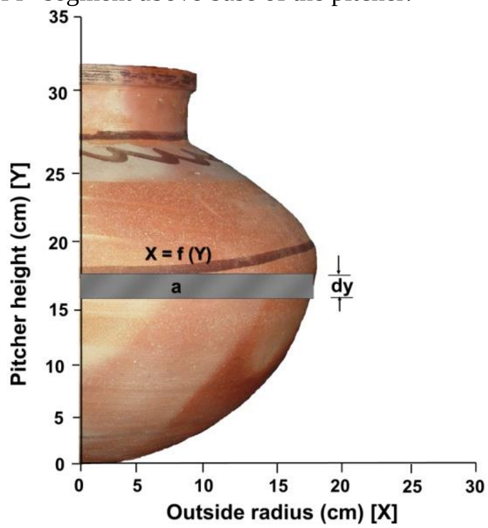

Figure 1: Illustration used in calculation of pitcher surface area

Pitcher wall density, saturated water content and soil porosity

The dry density of pitcher walls was calculated by dividing its oven dry weight with the volume of wall (pitcher surface area multiplied by wall thickness) as given in equation 3.

$$\rho_d = \frac{W_d}{A\,L} \text{x}100 \quad (3)$$

where ρ_d is dry density of pitcher, A is surface area and L is the wall thickness of pitcher. The saturated water content of pitcher walls was determined by placing pieces of pitcher in water for three days for saturation then their saturated weight was determined using the weighing balance. Dry weight of pitchers was also recorded after drying them in oven at 105 ^{o}C for 36 hours. The water content in pitchers at saturation on a weight basis (θ_m) was determined by gravimetric method using relation 4.

$$\theta_s = \frac{W_w - W_d}{W_d} \text{x}100 \quad (4)$$

$$n = 1 - \frac{\rho_d}{\rho_w} \quad (5)$$

where θ_s is water content in percent in pitcher wall at saturation; W_w is weight of saturated piece of pitcher wall; W_d is oven dry weight of piece of pitcher wall; n is porosity of pitcher wall and ρ_w is the density of water.

Pore size

Pore size of pitchers from both categories was determined using Scanning Electron Microscope (SEM). Two specimen, one from each category, were prepared and scanned using SEM (TM-1000, Hitachi).

Saturated hydraulic conductivity

The hydraulic conductivity at saturation of pitchers was measured by the falling head method as described by Abu-Zreig [10]. Before measurements, whole pitcher was saturated for three days. The pitcher, full of water, was then submerged up to its neck in a container (bucket) with constant water level maintained by an overflow. A graduated manometer tube of 1cm diameter was inserted into a hole drilled in the pitcher lid. The lid was then waxed with the mouth of pitcher with plaster of Paris so as to fasten the mouth of the pitcher air tightly as shown in Figure 2.

Water was filled in the manometer tube, which created hydraulic head difference across the pitcher's wall equal to the height of water level in the manometer above water surface in the bucket. The rate of drop in water height in the manometer due to seepage from the wall of the pitcher was monitored and recorded with elapsed time. The hydraulic conductivity at saturation was the determined by using equation:

$$K_s = \frac{\alpha l}{At} \text{x} \ln \frac{h_o}{h_t} \quad (6)$$

where h_o is the initial height of water in the manometer tube above the free water level in bucket, h_t is the height of water in the manometer tube after time t, α is the cross-sectional area of the manometer tube, L is the average wall thickness of the pitcher, K_s is the saturated hydraulic conductivity of pitcher.

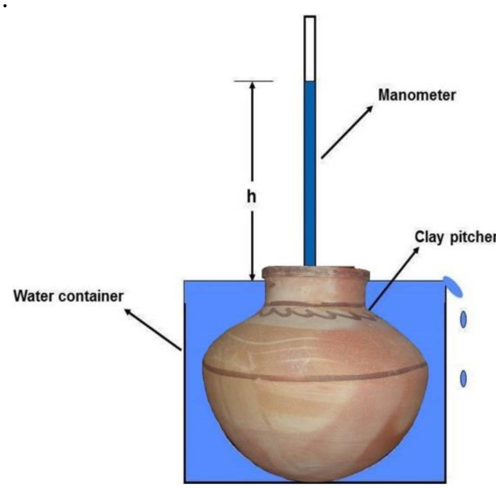

Figure 2: Schematic of the falling head permeameter setup

Radius of the soil wetting front

A piece of land was prepared to a fine tilth in which six holes of about two times wider and deeper than pitcher size were dug with distance of 2 m between them. Soil samples from the experimental area were randomly taken from the soil depths of 0-20 cm, 20-40 cm and 40-60 cm with the help of auger. These samples were analyzed for determining soil texture and dry density. Pitchers from both categories were buried in the soil down to neck. Their mouth openings were kept 2 cm above the soil surface which were covered with baked clay lids so as to avoid evaporation. Pitchers were refilled after every 24 hours and the volume of water needed to bring the level to the initial level was recorded. Four tensiometers per pitcher were installed at the depth of 15 and 25cm and at distances of 25 cm and 40 cm from pitchers. The tensiometer gauge readings were taken every day in the morning and afternoon for five days. From tensiometeric readings of soil moisture potential and the physical observations of the surface, the size of soil wetting zone around buried pitchers was determined [13].

RESULTS AND DISCUSSIONS

Physical parameters of pitcher

The geometrical dimensions and physical description of the all six pitchers used in the study are summarized in the Table 1. The table shows that pitchers in category *A* have average water holding capacity of 18.55±0.19 liters, height of 30.27±0.61 cm, wall thickness of 1.26±0.02 cm, wall porosity of 0.37±0.01, wall dry density of 1.53±0.01 g/cm^3, surface area of 2863±437 cm^2 and the saturated hydraulic conductivity (K_s) of 0.11±0.01 cm/day. Whereas, pitchers in category *B* have average water holding capacity, height and surface area similar to pitchers in category *A*, but different pitcher wall thickness, porosity, dry density and saturated hydraulic conductivity *viz.* 1.98±0.06 cm, 0.31±0.01, 1.59±0.01 g/cm^3 and 0.06±0.01 cm/day respectively. Statistical analysis of data of both categories of pitchers revealed that the saturated hydraulic conductivity of pitchers in category *A* was significantly ($p< 0.01$) higher than those of in category *B*. Similarly, there was highly significant ($p< 0.01$) difference in wall thickness, porosity, dry density of pitchers in both categories. Thus, pitchers in category *B* have significantly greater wall thickness, wall density but low porosity compared to pitchers in category *A*.

Figure 3 shows the pore size distribution in the wall of pitchers of both categories. It is clear from the scanned images that pitchers in category *A* have pores of size of about 10 μ m, whereas those in category *B* have pores of size of about 5 μ m. Thus, the size of pores in category *B* is only half of the size of those in pitchers in category *A*.

Soil texture and dry density

Textural class and dry density of soil where experiments of water seepage from pitchers and resulting radius of wetting zone were conducted, are given in Table 2. It shows that the textural class of soil profile from surface down to 60 cm was sandy loam with an average dry density of 1.40±0.01 g/cm^3.

Radius of wetting front

When the pitcher is filled, water oozes out of the pitcher through the micro-pores of the pitcher wall due to pressure head gradient between the water pressure head within pitcher and the adjacent soil (mostly negative pressure) resulting in axisymmetric advancement of wetting front in the soil root zone. An average volume of water seeped from the pitchers in sandy loam soil and infiltrated into soil in 24 hours and the resulting daily radius of wetted zone presented in the Table 3. It shows that radius of soil wetting zone is more for pitchers having higher porosity and hydraulic conductivity and thus higher seepage rate and greater size of wetting zone. Though both categories of pitchers had same size yet the water seeped from pitchers in category *A* was 31% more than that of from pitchers in category B. Also size of wetted zone after 5 day to initiation of seepage was about 22% greater for pitchers in category *A* than to that of category *B* pitchers.

Relation between pitcher wall thickness, porosity, K_s and wetting front

The radius of soil wetting front after five days to initiation of irrigation was plotted against the saturated hydraulic conductivity of the pitchers as shown in Figure 4. The regression analysis of data showed that there was a good relation between radius of soil wetting front and the saturated hydraulic conductivity of pitchers with coefficient of determination of R^2 = 0.903 (Figure 2). This relation can statistically be expressed by equation as:

$$RW = 17.81+118.34\,K_s \qquad (7)$$

The correlation between porosity of pitcher wall and the radius of soil wetting front after five days to initiation of seepage is visualized by plotting radius of soil wetting front against porosity of pitcher wall as shown in Figure 5. The plot shows that radius of soil wetting front is directly related to porosity of pitcher wall. Regression analysis of data showed positive relation between porosity of pitcher wall and the radius of soil wetting front with coefficient of determination of R^2 = 0.920.

Relation between pitcher wall porosity and saturated hydraulic conductivity

The relation of the pitcher wall porosity and its hydraulic conductivity was also envisaged by plotting values of both parameters against each other (Figure 6). It shows that saturated hydraulic conductivity increased with the increase in porosity of the pitcher wall. Thus, the higher the porosity of pitcher wall, the greater the hydraulic conductivity of pitcher. A positive linear relation between pitcher wall porosity and hydraulic conductivity was observed with coefficient of determination of R^2 = 0.917. These results are in accordance with Mondal [12].

Both categories of pitchers had same size (volume), height and surface area but the pitcher wall had different thickness, porosity and dry density. The variation in properties of pitcher walls of both categories may be due to variation in production temperature during pitcher firing process in the kiln. The production temperature is reported [10] to have a significant effect on the pore size as well as saturated hydraulic conductivity of pitchers. Abu-Zreig [11] reported that the porosity of pitcher wall depends on the pitcher materials (proportion of sand and clay) and firing temperature. In Pakistan, in some cases donkey dung is also mixed with pitcher material (sand and clay mixture) to increase the porosity of the pitcher wall [4]. Thus, through use of appropriate pitcher material (mixture), firing temperature in kiln and duration of firing, the hydraulic properties of the pitchers can be improved.

Effect of saturated hydraulic conductivity of pitcher wall on radius of soil wetting front, envisaged in the Figure 4, shows a positive linear relationship which reflects the significance of pitcher hydraulic conductivity in development of favorable soil moisture environment in the plant root zone. Similar results were reported by [4, 11, 13] for pitchers of three different sizes. Hydraulic conductivity of pitcher wall is directly related to wall porosity (R^2 = 0.917). Thus, for pitchers with higher porosity should have greater saturated hydraulic conductivity. These results are in accordance with

Mondal [12]. The success of pitcher irrigation system completely depends on the hydraulic properties (hydraulic conductivity, seepage rate and conductance) of the pitcher wall and these properties can be enhanced through use of appropriate pitcher material (sand clay ratio), and maintaining suitable firing temperature and firing interval in the kiln. An accurate placement of pitcher in soil is also important. It is suggested that before field installation, pitcher hydraulic properties and radius of soil wetting zone should be estimated as it will help in deciding placement distance between the pitchers so that wetted zones do not overlap.

Table 1. Physical characteristics of pitchers used in the study

Pitcher Name	Volume (lit.)	Height (cm)	Wall thickness (cm)	Porosity	Dry density (g cm^{-3})	Surface area cm^2	Hydraulic conductivity (cm day^{-1})
A1	18.5	30.0	1.30	0.36	1.52	2800	0.120
A2	18.7	31.0	1.25	0.37	1.53	2900	0.098
A3	18.4	29.5	1.26	0.39	1.54	2850	0.130
A4	18.6	31.2	1.25	0.38	1.53	2950	0.130
A5	18.9	30.5	1.26	0.35	1.52	2850	0.100
A6	18.2	29.4	1.25	0.36	1.55	2830	0.110
Mean	**18.5±0.19**	**30.2±0.61**	**1.26±0.02**	**0.37±0.01**	**1.53±0.01**	**2863±42**	**0.114±0.01**
B1	18.2	31.0	2.1	0.32	1.58	2770	0.062
B2	18.8	31.0	1.9	0.31	1.57	2950	0.055
B3	18.5	30.5	2.0	0.30	1.60	2820	0.060
B4	18.3	29.5	1.9	0.30	1.60	2825	0.059
B5	18.6	29.8	2.0	0.31	1.59	3000	0.060
B6	18.7	30.0	2.0	0.32	1.61	2825	0.062
Mean	**18.5±0.19**	**30.3±0.51**	**1.98±0.06**	**0.31±0.01**	**1.59±0.01**	**2865±71**	**0.060±0.01**

± Confidence Interval

Table 2. Soil texture and dry density of the soil

Sampling depth (cm)	Dry density (g/cm³)	% of soil separates			Textural Class
		sand	silt	clay	
0-20	1.42	56.0	27.0	17.0	Sandy loam
20-40	1.40	65.5	20.0	14.5	Sandy loam
40-50	1.39	69.0	12.0	19.0	Sandy loam

Table 3. Pitcher seepage rate and the radius of soil wetted zone

Pitcher Name	Seepage rate in soil (ml day^{-1})	Mean radius of wetting (cm day^{-1})	Cumulative radius of wetting after five days (cm)
A1	3350	6.1	30.5
A2	3448	6.3	31.5
A3	3100	6.4	32.0
A4	3500	6.8	34.0
A5	3400	6.3	31.5
A6	3300	6.0	30.0
Mean	**3349±112**	**6.3±0.22**	**31.5±1.11**
B1	2403	5.3	26.5
B2	2210	4.8	24.0
B3	2305	4.9	24.5
A4	2200	4.7	23.5
A5	2290	4.9	24.5
A6	2380	5.1	25.0
Mean	**2298±67**	**4.9±0.17**	**24.6±0.8**

± Confidence Interval

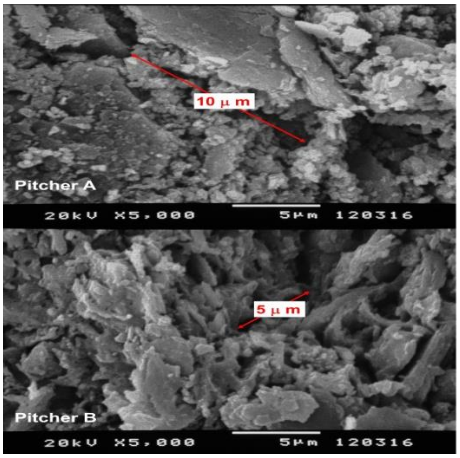

Figure 3: Pore size distribution of both categories of pitchers (Photos taken with Scanning Electron Microscope)

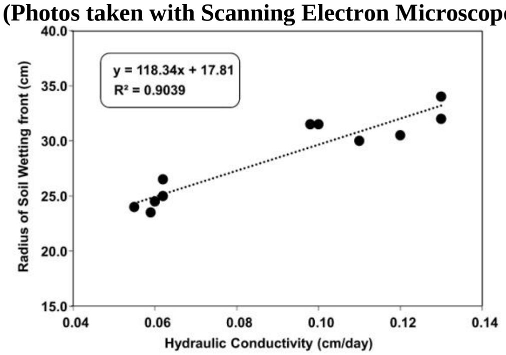

Figure 4: Radius of soil wetting front after five days plotted against hydraulic conductivity of pitcher

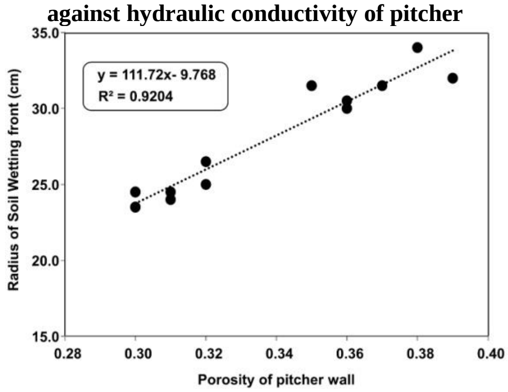

Figure 5: Radius of soil wetting front plotted against porosity of pitcher wall

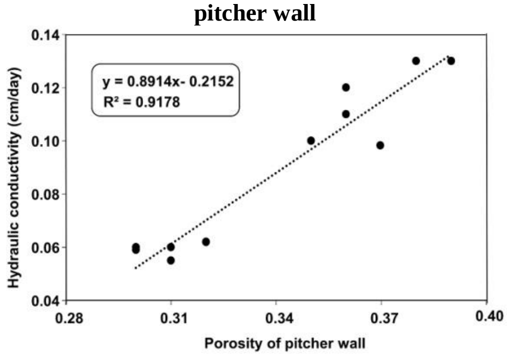

Figure 6: Porosity of pitcher wall plotted against saturated hydraulic conductivity

CONCLUSION & RECOMMENDATION

Hydraulic conductivity of pitcher wall has a pronounced effect on the size of wetting front as it plays a vital role on the volume of water seeped out from the pitcher. The results of study showed that the size of soil wetting front, after 5 days to initiation of seepage, was 22% more for pitchers in category A than to those in category B though both categories had pitchers of same size but the hydraulic conductivity of the pitchers in category A was nearly twice of those in Category B. Therefore, it is recommended that before field installation of pitchers, the radius of soil wetting front and the seepage rate should be determined as it will not only help in deciding the placement distance between the pitchers to avoid any overlapping of wet areas but it will also produce better soil water environment in the root zone.

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