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Creating Clay emitters for Low-Head Subsurface Irrigation

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ABSTRACT

The most precious resources on the planet are water and energy. It is important to develop new irrigation systems that are both creative and effective in their use of these resources. This research aims to develop a clay emitter based low-head subsurface irrigation system. The clay emitters CE1, CE2, and CE3 were designed as hollow cylindrical shapes with organic matter ratios of 1%, 2%, and 4%, respectively. The emitter's hardness and hydraulic properties, as well as the effect of soil type on its discharge and wetness zone, were examined. By increasing the organic ratio, the hardness was lowered, and the discharge was improved. Hydraulic parameters were measured in ambient air at pressure heads ranging from 0.2 to 1 m. According to the determined emitter discharge exponents (x), all types of flow are generally mostly turbulent or pressure compensating. The manufacturer's variation (*CV*) values for all types varied between marginal and unacceptable classification due to its manual fabrication. The emitter was placed at a depth of 10 cm in the soil, and the average discharge and wetness zone were higher in sandy loam than in sand soil over a four-day period of irrigation at 1 m pressure.

Keywords: Subsurface, Clay emitter, Hardness, Hydraulic Properties, Wetting Zone.

INTRODUCTION

With the increasing demand for fresh water around the world, the agricultural sector is the most consuming water. Irrigated agriculture represents 20 percent of the total cultivated land and contributes 40 percent of the total food produced worldwide (Waalewijn *et al.*, 2019). Modern irrigation systems with high water use efficiency consume significant energy input. Innovative irrigation techniques are still needed to obtain high water efficiency with low energy consumption (Adu *et al.*, 2019; Nogueira *et al.*, 2021; Zhang *et al.*, 2021). Water-saving irrigation technology such as subsurface irrigation, with water distribution emitters installed below the soil surface, maintains the soil surface relatively dry, reduces evaporation losses, improves crop yields, increases water use efficiency, and reduces labor. However, high energy requirements may cause environmental damage, high capital costs, clogged emitters by roots, and increased maintenance requirements (Sampson & Perry, 2019; Wang *et al.*, 2019; Xiao *et al.*, 2021). Subsurface irrigation by devices like pot is a water-saving technology. The buried clay pot filled with water is one of the most efficient conventional irrigation systems known with no external inputs (such as oil and electricity) without environmental impacts. The water seeps through the wall of the buried clay pot at a rate that is influenced by the plant's water use. This results in very high efficiency, better than drip irrigation, and 10 times better than traditional surface irrigation. This technology could provide a solution to future water crises around the world (Pachpute, 2010). The disadvantages of buried clay pots include their cost, size, installation time, flexibility, and breakage. The use of this method is more suitable for small-scale and labor-intensive irrigated agriculture, and its widespread use requires a reservoir and pipelines (Paredes and José 2019). However, in most developing countries due to manual manufacturing of pitchers, pots, it is difficult to obtain a low deviation (Vasudevan *et al.*, 2014). Therefore, there is a need to improve the structures and material properties of pots (Siyal *et al.*, 2016).

Subsurface irrigation with devices such as pots has recently been implemented using ceramic emitters to meet modern irrigation requirements. It has similar components to a subsurface drip irrigation system, and it does not need pumps, and the irrigation water flows from a constant pressure water tank (Cai *et al.*, 2017; Lamm & Trooien, 2003). Ceramic emitters do not clog by root intrusion due to their small pores (between 0 and 10 µm) which are used to seepage irrigation water (Cai *et al.*, 2018). The preferred operating pressure head for ceramic emitters is usually less than 100 cm and greater than or equal to 20 cm. As a result, the emitter discharge is minimal, the variance is low, and the distribution is uniform, ensuring that the root zone is kept at a suitable water level (Cai *et al.*, 2021; Kacimov & Obnosov, 2017). It is a non-pressure compensated emitter since the ceramic emitter discharge exponent is 1 (ASABE EP405.1 2003).

This research aims to develop an effective, environmentally clay emitter for modern low-head subsurface irrigation to increase water efficiency. To achieve this specific goal, research focuses on evaluating manufactured emitter types in the following areas:

- Reliability.
- The emitter's hydraulic properties in air and soil.
- The wetting patterns.

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MATERIALS AND METHODS

The most significant factors influencing water leakage from clay emitters have been highlighted. Manufacturing of emitters, as well as the effect of pressure and soil type on them.

Clay emitter manufacturing

The clay emitter characteristics are the main determinants of its water seepage. The following manufacturing points were highlighted:

The important factor in choosing the desired shape is the surface area to seepage water from the clay emitter. The expanded contact surface area with soil is preferable to achieve more water seepage. A hollow form of the emitter with a length of 10 cm is suggested as it can hold water with a large surface area in contact with the surrounding soil, Figure (1). Four proposed hollow shapes of the emitter were studied to choose the best shape considering the surface area of contact with the surrounding soil. The proposed shapes studied were cube, spherical, conical, and cylindrical. The surface area of these shapes was calculated to multiple-cavity sizes using engineering equations. The cylindrical shape was the best in the surface area of small sizes, in addition to its simplified practical shape, as shown in Figure (1).

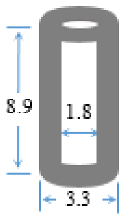

Figure 1. Sketch of a clay emitter and its dimensions in centimeters.

Three types of hollow cylindrical clay emitters were handcrafted by mixing fine straw with clay (bentonite) in specific proportions with the same dimensions as the inside diameter of the cavity, wall thickness, and length. Straw is the dry stem of agricultural cereal crops after the grain is harvested. Bentonite is an aluminum phyllosilicate clay that is mostly composed of montmorillonite.

The first type of clay emitter (CE1) was manufactured by 1% of straw and bentonite by 99%, in the second type (CE2) the proportion of straw doubled to 2% while the bentonite was 98%, the straw ratio was doubled for the second time in type (CE3) to 4% with 96% for bentonite.

The mixture was made as dough by adding water then pressing the wet mixture inside the plastic module. Then, moisture emitters were spread at room temperature for one day to primary drying. Finally, the primarily dried emitters were burned in the oven. The average dimensions of burned emitters are 8.9 cm long with 1.8 cm inner diameter and 3.3 cm outer diameter. The emitter is located at a depth of 10 cm and connected with the lateral pipe by a T-connector.

Hardness

To exam, the emitter type's reliability, its pressure resistance (stress load to deformation, fracture, crash, or collapse) was tested at Material Laboratory. The hardness of the emitter model is determined by the maximal axially directed compressive force required to crush it.

Clay emitter Discharge

a) Discharge versus pressure.

A laboratory experiment was conducted to find the water discharge of the three types of clay emitters under different pressures to determine the parameters of their discharge equation. Figure (2) shows the schematic diagram of the emitter hydraulic test bench. The bench consists of three polyethylene laterals pipes with an inside diameter of 16 mm and 1.8 m in length.

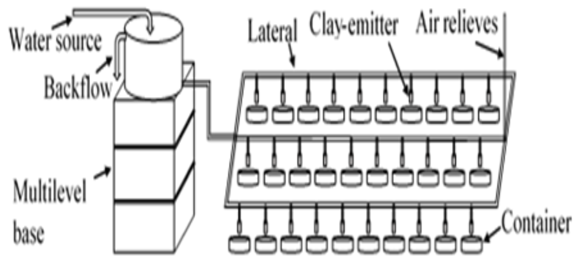

Figure 2. Schematic diagram of the clay emitter hydraulic test bench

Ten emitters of the same type were mounted on each lateral at an interval distance of 15 cm. The pipes network was a closed system, with both inlet and outlet pipes connected and the main pipe connecting them to the water supply. By adjusting the tank base height and attaching a backflow pipe adjacent to its tip, the water level in the tank was used to determine various pressure heads of 0.2, 0.4, 0.6, 0.8, and 1 m. Any air pockets that may have formed due to low pressure have been removed by connecting the air relief tube at the end of the pipelines. In plastic catchment gradual containers, water was collected from the emitters.

The empirical equation (Keller & Bliesner, 1990) that characterizes the discharge of emitters is:

$$\mathbf{q} = \mathbf{k}\, h^{x} \dashrightarrow (1)$$

Where:

q : calculated emitter discharge in ℓ/h,
h : pressure head in m,
k : emitter flow rate constant and
***x* : the discharge exponent that can be calculated using the slope of the q (Y-axis) against h (X-axis) curve.**

b) Coefficient of manufacturer's variation

The difference in the discharge of new random sample emitters when working at the same pressure due to manufacturing quality is the coefficient of manufacturer's variation (*CV*), and is expressed as:

$$\mathrm{Cv} = \frac{\mathrm{SD}}{q_a} \dashrightarrow (2)$$

$$q_a = \frac{1}{n}\sum_{i=1}^{n} q_i \dashrightarrow (3)$$

$$\mathrm{SD} = \left[\frac{\sum_{i=1}^{n}(q_i - q_a)^2}{n-1}\right]^{1/2} \dashrightarrow (4)$$

Where:

SD : the standard deviation of the emitter discharge rate.
q_a : the average value of the emitter discharge rate.
n : the total number of emitters along the lateral, and
q_i : the discharge rate of the emitter.

Soil analysis

Soil samples were collected and analyzed at a root depth of 0 - 60 cm to determine the soil's physical and chemical characteristics. Two soil samples were collected and air-dried before being crushed with a wooden pestle and mortar so that they could move through a 2 mm mesh screen (sieve). The fine soil particles that passed through a 2 mm sieve were packed into a plastic jar and analyzed chemically and physically.

Table 1. Physical and chemical properties of the soils tested.

Soil	Texture	EC dSm^{-1}	pH 1:2.5	Cations (meq/l)				Anions (meq/l)		
				Ca^{2+}	Mg^{2+}	Ca^{2+}	Mg^{2+}	Cl^{-}	HCO^{3-} + $CO3^{2-}$	$SO4^{2-}$
A	Sand	0.8	8.1	2.5	0.4	4.8	0.4	2.2	2.6	3.5
B	Sandy loam	0.4	7.8	2.1	0.5	2.0	0.19	2.0	1.5	1.1

The physical and chemical characteristics of the soils analyzed are summarized in Table (1). The electrical conductivity (EC) of the saturation soil paste extract was measured. The pH of the soil was measured in deionized water (in 1: 2.5 suspension). The pipette methods were used to analyze and evaluate the particle size distribution (Gee & Bauder, 1979).

Wetting Patterns.

The saturated hydraulic conductivity and wetting zone calibration experiments were conducted for the three emitter types in sand and sandy loam soils. The water source consisted of a tank with a one-meter constant water level head above the emitters, which was connected to the main pipe and split into three lateral pipes with a two-meter internal distance. Fifteen new emitters of each type were tested, with five emitters attached to each lateral pipe at a depth of 10 cm below the soil surface. Measurements were taken every day during the four-day irrigation process.

The soil wetting pattern depends upon emitter discharge and soil properties. Water seeps through the porous walls of the clay emitter due to static pressure and suction from the soil, while gravity and capillary forces moisturize the root zone vertically and horizontally. Most of the time, the low-head irrigation system was turned on. As a result, the irrigation system's running time influenced emitter discharge and the wetting zone. The diameter and depth of wetted soil around emitter types were measured after one and four irrigation days in the two soil types of sand and sandy loam, as described in Figure (3), and the wetness zone was computed using the equation of Schwartzman and Zur 1986:

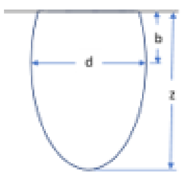

Figure 3. The diameter and depth of the emitter's wetted zone.

$$V = \frac{\pi}{12}\, d^2 + \left[2z + h - \frac{h^3}{(z-h)^2}\right] \dashrightarrow (5)$$

Where:

V : the wetted soil volume predicted (cm^3),
d : the maximum diameter of the wetted soil volume (cm).
z : maximum depth (vertical extent of wetting volume) (cm).
h : the distance from maximum diameter up to the wetted soil surface (cm).

RESULTS AND DISCUSSIONS

Hydraulic Characteristics of Clay Emitters

Effects of operating pressure on discharge, flow equation constants (k and *x*), and manufacturer coefficient variation (%) of emitter types are shown in Table (2) as the results of a laboratory experiment in ambient air. The relationship between operating pressure and emitter discharge is represented in Figure (4). By raising the pressure head from 0.2 to 1 m, the discharge of CE1, CE2, and CE3 was increased by 24.4% (from 0.31 to 0.99 L/day), 6.85% (from 1.04 to 1.39 L/day), and 4.5 percent (from 1.37 to 1.64 L/day). The *x* value of emitter CE1 is 0.76 which is classified as mostly turbulent flow. While it is classified as pressure compensation with *x* values of 0.17 and 0.11 for CE2 and CE3 respectively according to (ASABE EP405.1, 2003).

When the pressure was increased from 0.2 to 1.0 m, as shown in Figure (5). CE1's *CV* ranged from 0.07 to 0.13, indicating that it was considered marginal to poor. The *CV* of CE2 increased from 0.15, which is considered poor, to 0.19, which is considered unacceptable. In the two pressures, the *CV* of CE3 was reduced from 0.57 to 0.35, which was deemed unacceptable (ASABE EP458 1999). The high *CV* values of clay emitters can be explained by their low operating pressure and hand-made structure.

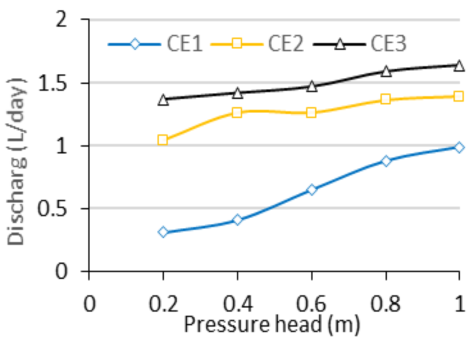

Figure 4. The impact of pressure on the discharge of emitters.

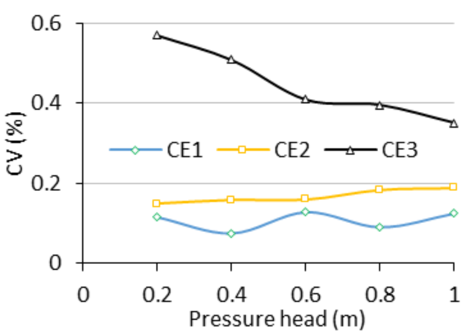

Figure 5. The manufacturer's coefficient of variation (*CV*) versus pressure for the emitters.

Table 2. Effects of operating pressure head on discharge, flow equation constants, and manufacturer coefficient variation (%) of emitter types.

Emitter type	Head (m)	q_{av}, L/h (L/day)	k	*x*	classification	*CV*	classification
CE1	0.2	0.01 (0.31)	0.97	0.76	Mostly Turbulent	0.12	unacceptable
	0.4	0.02 (0.41)				0.07	
	0.6	0.03 (0.65)				0.13	
	0.8	0.04 (0.88)				0.09	
	1	0.04 (0.99)				0.12	
CE2	0.2	0.04 (1.04)	1.41	0.17	Pressure Compensating	0.15	poor
	0.4	0.05 (1.26)				0.16	unacceptable
	0.6	0.05 (1.26)				0.16	unacceptable
	0.8	0.06 (1.36)				0.18	unacceptable
	1	0.06 (1.39)				0.19	unacceptable
CE3	0.2	0.06 (1.37)	1.61	0.11	Pressure Compensating	0.57	marginal
	0.4	0.06 (1.42)				0.51	marginal
	0.6	0.06 (1.47)				0.41	poor
	0.8	0.07 (1.59)				0.40	marginal
	1	0.07 (1.64)				0.35	poor

Reliability

The hardness of the emitter, as shown in Figure (6), is a reliable measure. The compressive force needed to split the emitters was reduced from 1879 to 1492 and 1204 N for CE1, CE2, and CE3, respectively. It means that for CE1, CE2, and CE3, the force/length needed to crack clay emitters were 21.6, 17.0, and 13.3 kN/m, respectively.

Consequently, it can be observed that increasing the organic matter in the emitter manufacturing process reduces the overall compressive force needed to split the emitters.

The Soil's Wetness Pattern

Accurate data on the wetting zone of clay emitters in the soil under low-head subsurface irrigation aids designers in determining the best interval distance and discharge to minimize system costs and improve soil water conditions for more efficient and effective water usage.

From sand to sandy loam soil, the average four-day discharge of CE1, CE2, and CE3 increased from 0.62 to 0.66 L/day, 0.68 to 0.92 L/day, and 0.83 to 1.70 L/day, respectively. Similarly, the witting zone diameter expanded from sand soils to sandy loam soils, where it was (15.7 to 17.8 cm), (17.94 to 25.8 cm), and (19.5 to 26.6 cm) for CE1, CE2, and CE3, respectively. The average discharge per unit time in the air was higher than in the soil for most of the emitter types. Since emitter discharge in soil was averaged over four days, soil saturation reduced emitter discharge over time. The gap between emitter discharge in air and soil was reduced by increasing the amount of straw in the emitters and using it in fine texture soils.

The wetness zone of all emitter types is shown in Figure (7) as a true function of the wet diameter, with the percentage increasing as the irrigation running duration increases. From one to four days, the volume of the wetness zone in sand soil increased by 52.0% with CE1 (from 63.1 to 95.9 cm^3), 44.4% with CE2 (from 77.3 to 111.6 cm^3), and 53.3% with CE3 (from 89 to 136.4 cm^3). Meanwhile, the wetness zone in sandy loam soils increased from 90.6 to 126 cm^3 (by 39.4%), 187.8 to 234.8 cm^3 (by 39.4%), and 202.7 to 249.9 cm^3 (23.3%) for CE1, CE2, and CE3, respectively. The results showed that altering the soil type from sand to sandy loam soil enhanced the wetness zone volume for all emitter types by increasing irrigation running duration from one to four days.

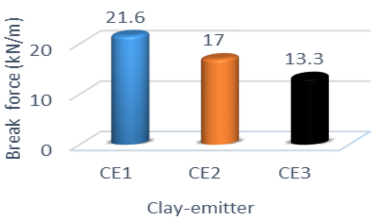

Figure 6. The force required to break clay emitters in kN/m.

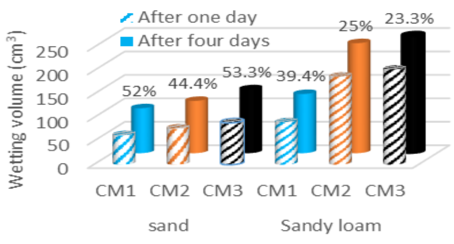

Figure 7. The impact of emitter type on the wetting zone in various soils and irrigation durations.

CONCLUSION

This research aided in the creation of a subsurface clay emitter with a low head. The emitter forms CE1, CE2, and CE3 were made of bentonite with straw ratios of 1%, 2%, and 4%, respectively. The compressive strength needed to split the emitters was reduced by increasing the straw ratio from 1879 to 1492 and 1204 N, respectively, for CE1, CE2, and CE3.

In atmospheric air, the hydraulic properties of the emitter were tested at pressure heads ranging from 0.2 to 1 m. The discharge was increased for CE1, CE2, and CE3 by raising the straw ratio and pressure from 0.2 to 1m as (0.31 to 0.99 L/day), (1.04 to 1.39 L/day), and (1.37 to 1.64 L/day), respectively. CE1 discharge exponent (*x*) of 0.76 indicated mostly turbulent flow, whereas CE2 (0.17) and CE3 (0.11) indicated pressure compensating flow. CE1, CE2, and CE3 had CV of 0.59 to 0.37 (unacceptable), 0.15 to 0.19 (poor to unacceptable), and 0.07 to 0.12 (marginal to unacceptable), respectively. The *CV* values evaluation falls into the lower classification category for all types due to its manual manufacturing.

The average four-day discharge of CE1, CE2, and CE3 increased from 0.62 to 0.66 L/day, 0.68 to 0.92 L/day, and 0.83 to 1.70 L/day, respectively, when the soil type changed from sand to sandy loam. Similarly, the witting zone diameter increased from sand to sandy loam soils, extending from (15.7 to 17.8 cm), (17.94 to 25.8 cm), and (19.5 to 26.6 cm) for CE1, CE2, and CE3, respectively. Based on the discharge and hardness requirements, the farmer may choose the appropriate clay emitter type.

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تصنيع منقطات فخارية للري تحت السطحي منخفض الضاغط

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المياه والطاقة هي أثمن الموارد على هذا الكوكب. من المهم تطوير أنظمة ري جديدة تكون مبدعة وفعالة في استخدامها لهذه الموارد. يهدف هذا البحث إلى تطوير نظام ري تحت سطحي منخفض الضاغط يعتمد على منقط فخاري. تم تصميم المنقط على شكل أسطواني مجوف وصُنع يدويًا من الطين (البنتونايت) مخلوط بثلاث نسب 1٪ و2٪ و4٪ من المادة العضوية (القش) لأنواع المنقط(CE1) ، (CE2)و (CE3) على التوالي .ثم فحص الصلابة والخصائص الهيدروليكية وتأثير نوع التربة على منطقة التصريف والترطيب لهذه الأنواع من المنقط. كان أحد المتطلبات لإمكانية الاعتماد عليها هو صلابتها، وجد أنه بزيادة نسبة القش قلت الصلابة، بمعنى مقاومتها لقوة الضغط اللازم لتقل القوة اللازمة للكسر من 1879 إلى 1492 و1204 نيوتن، لأنواع المنقطCE1 ، CE2و CE3على التوالي .تم تقييم خصائص المنقط الهيدروليكية في الهواء الجوي عند ضواغط تشغيل متدرجة من 0.2 إلى 1 متر. فكان هناك بالمقابل تدرج في زيادة التصرف للمنقطات من CE1 الى CE2 ثمCE3 ، من 0.31 إلى 0.99 لتر/ يوم، من 1.04 إلى 1.39 لتر/ يوم، ومن 1.37 إلى 1.64 لتر/يوم على التوالي. وأظهرت نتائج أس تصرف المنقطات (x) المحسوبة اختلاف تصنيف سريانها. حيث كان أس تصرف (x)المنقطاتCE1 ، CE2وCE3 بقيمة 0.76، 0.17 و0.11، على التوالي، مما يشير في الغالب إلى سريان مضطرب لـ CE1 ومعوض للضغط لـ CE2 و .CE3بينما كان معامل اختلاف التصنيع CV للمنقطاتCE1 ، CE2و CE3يتراوح من 0.07 إلى 0.12 (هامشي إلى غير مقبول)، و0.15 إلى 0.19 (فقير إلى غير مقبول)، و0.59 إلى 0.37 (تصنيفه غير مقبول)، على التوالي، ويلاحظ أن تصنيف قيم CV المتدني لجميع أنواع المنقطات بسبب تصنيعها اليدوي. من ثم تم قياس التصرف ومنطقة الترطيب للمنقطات في تربة رملية ورملية لوميه على عمق 10 سم من سطح التربة، وذلك بعد مدة يوم و4 أيام من تشغيل الري تحت ضغط 1 متر. وكان متوسط التصرف (0.15 و0.175 لتر/ يوم)، (0.175 و0.225 لتر/ يوم) و(0.2 و0.425 لتر/ يوم) للمنقطاتCE1، CE2 وCE3، على التوالي. وأظهرت النتائج زيادة تصرف المنقط الفخاري في الهواء الجوي عنه في التربة بالرغم من تعرضه لقوى شد أعلى في التربة عن الهواء الجوي وذلك يعود لكون متوسط التصرف في الهواء الجوي لا يتأثر بطول المدة لكن متوسط أربعة أيام ري في التربة يقل التصرف بزيادة المدة وانخفاض قوى الشد نظراً لتشبع التربة. وزاد حجم منطقة الترطيب بعد أربعة أيام في كلا من التربة الرملية-اللوميه والرملية بنسبة 39.4٪، 25٪ و23.3٪ وبنسبة 53٪، 53.3٪ و53.3٪ للمنقطات CE1، CE2 وCE3 على التوالي. وأشارت هذه النتائج لزيادة متوسط التصرف وحجم منطقة الترطيب للمنقطات في التربة الرملية-اللوميه عن الرملية. ويوصى بناءً على متطلبات التصرف والصلابة أن يختار المزارع نوع المنقط الفخاري الأنسب له.