

Drip Irrigation System Using Porous Ceramic Emitters With Different Soil Fraction Compositions

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ABSTRACT

This study investigated the optimal clay–sand ratio for producing porous ceramic emitters with efficient water distribution. Experiments were conducted at the Soil and Water Laboratory, Sriwijaya University, using a randomized block design with five treatment clay-sand mixture ratios: P1 (1.5:1), P2 (1.25:1), P3 (1:1), P4 (1:1.25), and P5 (1:1.5), with each treatment replicated three times. Water discharges for each treatment were 0.02 l.h⁻¹, 0.05 l.h⁻¹, 0.1 l.h⁻¹, 0.20 l.h⁻¹, and 0.60 l.h⁻¹. The composition of clay and sand in the manufacture of porous ceramic emitters affected the distribution of water horizontally (H), vertically above the drip line (Va), and vertically below the drip line (Vb), as well as the ratio of the distance of water distribution below the drip line (H/Vb). The emitter with the highest sand composition (P5) exhibited horizontal water distribution distances of 13.95 cm, 10.52 cm, and 13.21 cm above and below the drip line, respectively. However, this emitter had the lowest ratio of horizontal water distribution distance to water distribution distance below the drip line (H/Vb), at 1.06. Increasing the amount of sand only affected the water distribution ratio below the drip line (H/Vb). The simulation results showed that all treatments had a horizontal-to-vertical water distribution ratio below the drip line equal to or greater than 1.0, which is one criterion for assessing a good water distribution pattern.

Keywords: Clay, drip lines, emitter composition, sand, water distribution

INTRODUCTION

Water shortages and the shrinking availability of fertile land have made it increasingly difficult for many farmers to grow vegetables. This makes it more urgent to find irrigation solutions that use water efficiently while still protecting soil and water resources. One promising approach is subsurface drip irrigation (SDI), which has gained popularity worldwide because it boosts yields while saving significant amounts of water, achieving application efficiencies of 50% to 95% (Ayar et al., 1999; Cao et al., 2021).

In regions where water supply is especially tight, such as during the dry season, SDI is a highly effective way to deliver water precisely where it's needed (Patra et al., 2022; Payero et al., 2016). Sustainable farming depends not only on having

enough water but also on helping farmers use it wisely—saving water without sacrificing yields (Jafari et al., 2021). Supplying water directly to the root zone is one of the most effective ways to improve harvests. For example, using SDI in vineyards increased production by 10% (Ma et al., 2020), and similar systems have shown better results than sprinklers. In sweetcorn, yields were 12–14% higher than with sprinkler systems (Firouzabadi et al., 2021; Phene & Sanders, 1976) and approximately 200% higher than those achieved with furrow irrigation (Bogle et al., 1989; Irmak, 2024; Khamees et al., 2023). In China, combining SDI with moderate fertilizer applications has resulted in peak corn yields (Zou et al., 2020). Other studies report yield gains of up to 12% and evapotranspiration reductions of 15% (Li et al., 2021; Zheng et al., 2025). Rice farmers have also seen yield increases of 155% due to better nitrogen uptake (Cui et al., 2025; Rana et al., 2023).

An SDI set uses driplines—polyethylene (PE) pipes fitted with emitters at set intervals—buried at depths determined by soil texture, crop type, and field machinery use. For instance, 0.2 m-deep driplines spaced 0.6 m apart have worked well for alfalfa (Cai et al., 2018). For shallow-rooted horticultural crops, depths of 0.1–0.2 m are standard (Devasirvatham, 2008; Hamad et al., 2022); however, deeper installations of 0.30–0.45 m have also been successful (Ayar et al., 1999; Büser et al., 2025). Sweet corn systems have ranged from 0.05 m (Phene & Sanders, 1976) to 0.45 m (Onken et al., 1979), while sugarcane tends to do best at 0.2–0.3 m (Dashteghol & Naseri, 2021). In onions, SDI has outperformed surface drip because it loses less water to evaporation (Biswas et al., 2015; Evett et al., 1995), with laterals placed at 15 cm and 30 cm able to store 5.1 cm and 8.1 cm of water, respectively.

Beyond standard Petri lines, researchers have experimented with porous ceramic emitters shaped like jars or pots (Naik et al., 2013) or porous ceramic tubes (Cai et al., 2018; Liu et al., 2011). Designing such systems often begins with infiltration tests under various operating conditions to understand how water moves through the soil, tracking cumulative infiltration, the wetting front, and soil moisture patterns (Assouline, 2019; ahin, 2023).

The rate at which water spreads from an emitter depends on several factors, including soil texture, bulk density, initial moisture levels, emitter design, and burial depth. Emitter features such as size, flow rate, and operating pressure (Kalashnikov et al., 2023) are essential. Flow rate itself depends not just on pressure but also on the ceramic's hydraulic conductivity (Ashraf et al., 2002; Patel and Rajput, 2007; Rasheed, 2023) and the soil's clay–sand balance (Mahler, 2024; Maury et al., 2024; Nogueira et al., 2021; Payero et al., 2016).

Once water leaves the emitter, it spreads outward along the dripline, upward toward the surface, and downward into deeper layers. Understanding and managing this water movement is key to keeping the rootzone hydrated without wasting water through evaporation or deeper percolation. This study aims to determine the optimal clay–sand mix for porous ceramic emitters, focusing on how drip lines in SDI systems distribute water underground.

MATERIALS AND METHODS

This study was conducted at the Soil and Water Laboratory Hangar, Department of Agricultural Engineering, Faculty of Agriculture, Universitas Sriwijaya. The primary materials for the ceramic

emitters were a mixture of clay and sand, with clay as the binding agent and sand as the strengthening material. The experiment followed a Randomized Complete Block Design (RCBD). The clay–sand compositions were as follows:

P1: 1.5 parts clay + 1 parts sand

P2: 1.25 parts clay + 1 parts sand

P3: 1 parts clay + 1 parts sand

P4: 1 parts clay + 1.25 parts sand

P5: 1 parts clay + 1.5 parts sand

Each treatment was replicated three times. We thoroughly mixed the clay and sand for each treatment, moistened them to a semi-plastic consistency, and hand-shaped them. Researchers can manufacture porous ceramics using various methods, including compression and extrusion (Cai et al., 2018; Vaghei et al., 2022). The emitters produced in this study were 9 mm in diameter and 12 mm in length.

After shaping, the damp emitters were air-dried for one week in an open, shaded area. They were then fired in a Mapple Furnace, with the temperature gradually increased to a maximum of 900 °C over 48 hours, followed by a 12-hour tempering stage. Increasing the sintering temperature from 900 °C to 1100 °C generally reduces porosity while increasing mechanical strength (Mouiya et al., 2019). Water distribution from the emitters was observed using air-dried soil placed in a transparent acrylic box measuring 60 cm (length) × 40 cm (width) × 45 cm (height). A dripline was installed lengthwise in the box and buried 10 cm below the soil surface. The soil used was Ultisol, air-dried to a moisture content of 13.5%, with a bulk density of 1.12 g·cm⁻³. The soil texture was sandy clay loam, consisting of 72.88% sand, 19.57% clay, and 7.65% silt (Novianti, 2013).

We observed wetting patterns for each treatment at an inlet pressure of 15 psi. Because emitter discharge rates varied with clay–sand ratios, operating times were not uniform: P1 ran for 90 minutes, P2 for 60 minutes, and P3, P4, and P5 for 30 minutes.

The measured parameters included:

H: Average horizontal wetting distance from the emitter

Va: Vertical wetting distance above the drip line

Vb: Vertical wetting distance below the drip line (wetting depth) **H/Va** and **H/Vb** ratios (Figure 1).

Supporting data included emitter discharge for each treatment, hydraulic conductivity measured using the falling head method, and initial soil moisture content measured gravimetrically.

After irrigation, we plotted the wetting pattern on standard graph paper. The horizontal

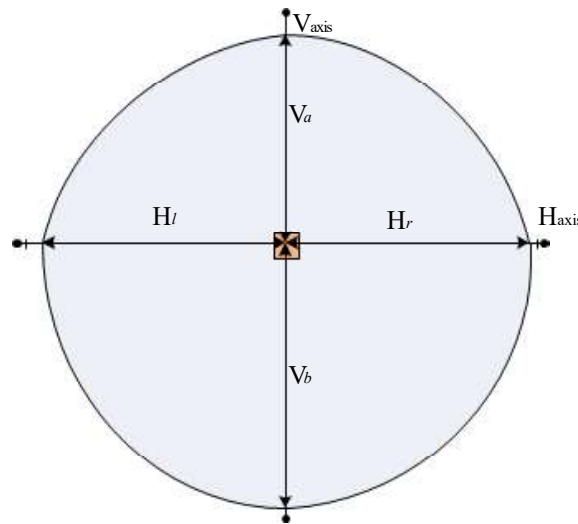


Figure 1. Two-Dimensional emitter wetting interface for wetting distribution measurement.

wetting distance (**H**) was measured from the point where the emitter's vertical axis intersected the wetting perimeter to the furthest edge of the wetted area. If the wetting widths on the left and right sides of the emitter's vertical axis were not symmetrical, we used the average of the two measurements as the horizontal wetting distance (**H**).

The vertical wetting distance above the dripline (**V_a**) was measured from the intersection of the horizontal and vertical axes upward to the highest point of the wetting perimeter. Meanwhile, the vertical wetting distance below the dripline (**V_b**)—or wetting depth—was measured from the same intersection point downward to the lowest point of the wetting perimeter.

RESULTS AND DISCUSSION

The vertical wetting distances above the dripline (**V_a**) and below the dripline (**V_b**) showed different ranges. Therefore, in the wetting-pattern analysis, we treated these measurements separately, using the dripline as the dividing reference. We obtained observational data on wetting characteristics for all treatments from predictions over 60 minutes. We then applied polynomial regression to model wetting patterns on both the left and right sides of the emitter. In general, the resulting wetting shapes resembled a half-circle (Skagg et al., 2004).

Horizontal and Vertical Wetting Front

The distribution of water from the emitters produced varying horizontal and vertical wetting distances, influenced by differences in emitter discharge rates, which were in turn affected by the

clay–sand composition used in each treatment. Treatments with higher sand content produced more porous emitters, resulting in higher discharge rates. The emitter made from a mixture of 1 part clay to 1.5 parts sand produced the highest discharge rate (10 mL min⁻¹, equivalent to 0.6 L h⁻¹). However, overall, all treatments had lower discharge rates than commercial emitters, even at pressures up to 15 psi. The lower discharge rates help control deep percolation, making them suitable for sandy soils. In porous ceramic emitters, clay–sand composition also affects discharge rate, in addition to operating pressure (Cai et al., 2021; Patel & Rajput, 2007).

Subsurface irrigation increased the water potential at the emitter position along the dripline. Under these conditions, the driving force for water movement acted in all directions, allowing water to move progressively away from the emitter. As soil moisture at the emitter location continued to rise, the matric potential gradient increased, enhancing multidirectional water movement. This increased the average horizontal wetting distance, while capillary forces promoted gradual upward wetting above the drip line. Conversely, gravity caused some water to move downward below the dripline into deeper soil layers. An emitter's ability to distribute water horizontally determines emitter spacing along the dripline, the number of emitters required, and, consequently, the initial investment and maintenance costs of the irrigation system. We obtained the average horizontal wetting widths for each treatment and replication from 60-minute irrigation predictions (Figure 2).

Treatment P5 showed a significant increase in horizontal wetting distance, reaching up to 13.95 cm

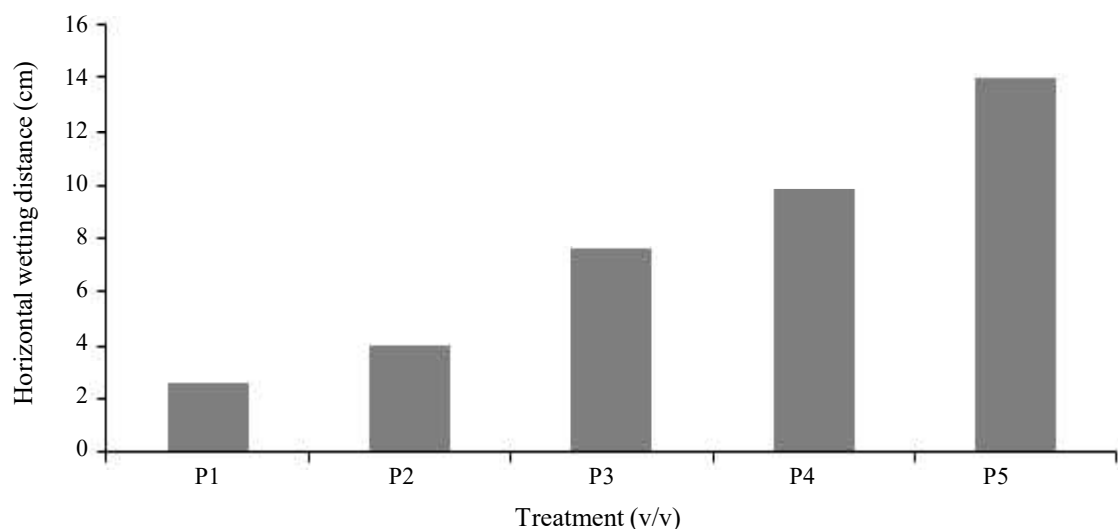


Figure 2. Horizontal wetting distance on each clay and sand composition treatment.

from the emitter position (Table 1). Higher initial soil moisture content leads to a larger wetting pattern in all directions (El-Nesret et al., 2014; Liu et al., 2011; Rasheed, 2023; Skaggs et al., 2004). For emitters with higher discharge rates, soil moisture increases more rapidly, water distribution occurs faster, and the wetting front becomes wider. However, several factors must be considered, such as soil physical properties, soil matric potential, and the effect of gravity on the wetting ratio above and below the drip line.

Horizontal water distribution can be improved by reducing emitter discharge and increasing irrigation duration (Cai et al., 2022; De Marchi et al., 2025). Using glow-discharge emitters improves horizontal water spread, controls percolation, determines emitter spacing along the drip line, and optimizes the number of emitters used. This, in turn, minimizes total costs for irrigation equipment procurement, as well as operation and maintenance expenses.

Water also infiltrates vertically, both above and below the dripline. Vertical wetting above the dripline (Va) is primarily driven by capillary forces associated with adhesion and cohesion. The vertical wetting distance above the dripline increased significantly when the soil composition was 50% clay and 50% sand (1:1 ratio, P3). This distance continued to increase, with the highest value of 10.52 cm observed in treatment P5, which used an emitter in soil with a clay-to-sand ratio of 1:1.5. A greater vertical wetting distance above the dripline can be advantageous in designing systems that place driplines deeper in the soil profile.

For vertical wetting below the drip line (Vb), treatment P5 also showed the deepest infiltration, reaching 13.95 cm from the emitter position (Figure 3). Beyond the emitter location, vertical wetting distance below the drip line gradually decreased because the soil matric potential gradient decreased and capillary forces diminished.

The ANOVA results indicated that clay-to-sand composition significantly affected both the horizontal wetting distance and the vertical wetting distances above and below the drip line. Furthermore, the LSD test results (Table 1) showed that the horizontal wetting distance increased significantly when the clay proportion decreased from treatment P1 (1.5 parts clay: 1 part sand) to treatment P2 (1.25 parts clay: 1 part sand). A rise also followed an increase in sand content in vertical wetting distance, both above and below the drip line; these two parameters are critical when determining drip-line placement depth to ensure it aligns with the crop's root-zone distribution.

Higher sand content can increase emitter discharge rates, making gravitational forces more dominant than matric potential gradients and capillary action. As a result, the wetting ratio below the dripline (H/Vb) decreases (Table 2). When soil continuously receives irrigation water from high-discharge emitters, the cumulative infiltration time at a constant infiltration rate becomes shorter. This condition can promote water migration and deeper percolation. In this study, we controlled percolation by applying a low emitter discharge rate, with a maximum of $0.6 \text{ l} \cdot \text{h}^{-1}$. Proper system design can reduce soil surface evaporation and percolation, preventing unnecessary water loss and improving water-use efficiency (Lamm et al., 2006; Zhao et

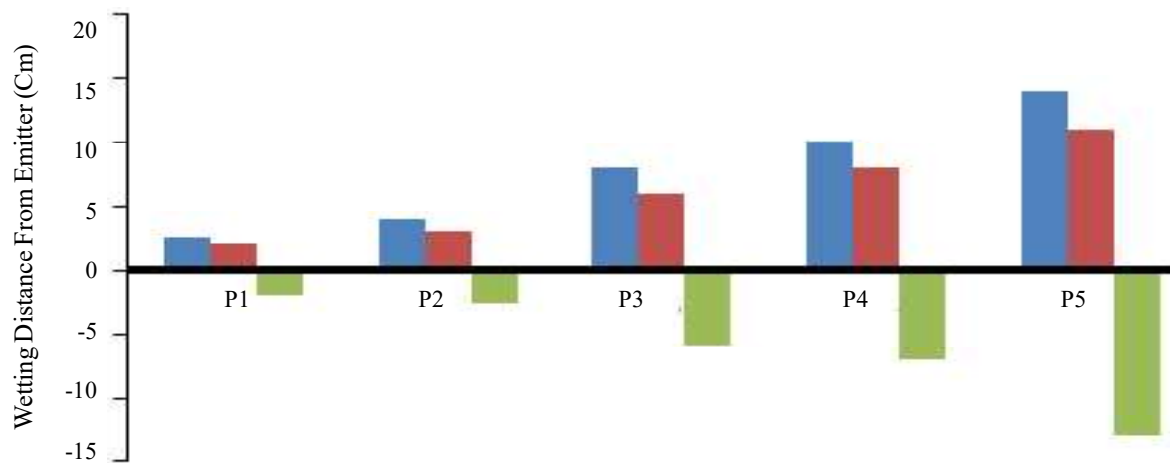


Figure 3. Wetting distance from emitters, which measured on the wet interface in the transparent simulator box. ■: Horizontal, ■: Vertical over dripline, ■:

al., 2024). To optimize subsurface drip irrigation, it is necessary to examine several operational parameters, such as irrigation frequency and duration, emitter discharge rate, emitter spacing, and dripline placement (Skagg et al., 2010). In addition to emitter discharge rate, soil texture and structure also influence water movement in the soil (Bresler, 1978; Kumar et al., 2021; Warrick, 1974). In soils with higher sand content, irrigation water more readily moves into deeper soil layers. Several studies show that soil texture is a key factor in irrigation design because it strongly influences infiltration. Therefore, subsurface drip irrigation system design must account for soil texture (Khoshravesh-Miangoleh & Kianii, 2014; Nagliæ et al., 2014; Patel & Rajput, 2009; Skaggs et al., 2010). Matching emitter discharge to soil conditions can mitigate vertical water migration below the rootzone (Ali et al., 2024; Patel & Rajput, 2007).

Wetting Distance Ratio

The wetting distance ratio from the emitter is defined as the ratio of horizontal wetting distance (H) to vertical wetting distance (V). These wetting characteristics are essential parameters in the design and operation of subsurface drip irrigation systems. Water distribution from the emitter should prioritize the horizontal direction while minimizing downward movement below the dripline. This approach maximizes the wetted area while controlling water loss through deep percolation. A wetting pattern is generally optimal when the ratio H/V_b is approximately 1, or at most $H/V_b = 1$. According to the study observations, the P5 treatment produced the H/V_b ratio closest to 1 (1.06). (Table 2). Furthermore, observations in this study indicate that

the H/V_a ratio increased consistently as the sand proportion in the soil composition increased, from 1.19 in P1 to 1.34 in P5 (Figure 4). This finding suggests that water movement remained more dominant horizontally, particularly when emitter discharge rates were kept low. The emitter discharge rates for P1, P2, P3, P4, and P5 were $0.02 \text{ l} \cdot \text{h}^{-1}$, $0.05 \text{ l} \cdot \text{h}^{-1}$, $0.09 \text{ l} \cdot \text{h}^{-1}$, $0.20 \text{ l} \cdot \text{h}^{-1}$, and $0.60 \text{ l} \cdot \text{h}^{-1}$, respectively. A study by Sharu and Razak (Sharu & Ab Razak, 2020) in Malaysia reported an optimal emitter discharge of $0.03 \text{ l} \cdot \text{h}^{-1}$, while $0.44 \text{ l} \cdot \text{h}^{-1}$ has been successfully applied in Nigeria (Akande & Oladejo, 2025). Increased soil moisture around the emitter creates a greater water potential difference, enhancing capillary action above the dripline and increasing upward driving forces. Initial soil water content plays a key role in determining water potential during the early stages of infiltration. Higher initial water content tends to increase the wetting pattern in all directions and improve its uniformity (Cai et al., 2018; El-Nesr et al., 2014; Liu et al., 2011; Skaggs et al., 2010). However, the trend for the H/V_b ratio differed: higher sand content resulted in a lower H/V_b ratio (Table 2).

The ANOVA results indicated that variations in clay and sand (P5) composition significantly affected the H/V_b ratio (Table 2), but had no significant effect on the H/V_a ratio. Higher sand content increases emitter discharge and can negatively affect the H/V_b ratio, as gravitational forces become more dominant than matric potential gradients and capillary forces. As shown in Table 2, the H/V_b ratio decreased significantly for the 1:1.5 clay-to-sand composition (P5). The H/V_b ratio is a crucial parameter, as a smaller ratio indicates that irrigation water penetrates deeper into the soil layers

Table 1. LSD test result on wetting horizontal distance response, average of vertical over drip line, and under drip line.

Wetting distance from emitters	LSD α 0,05	P1	P2	P3	P4	P5
Horizontal*	1.28	2.54 ^a	3.99 ^b	7.61 ^c	9.88 ^d	13.95 ^e
Vertical Over Drip Line*	2.03	2.15 ^a	3.25 ^{ab}	6.02 ^b	9.19 ^c	10.52 ^d
Vertical Under Drip Line*	3.66	1.94 ^a	3.19 ^a	6.91 ^b	8.02 ^b	13.21 ^c

* = Recorded from the simulation irrigation result during 60 minutes

Table 2. Ratio of horizontal wetting distance to vertical wetting distance below the drip line (H/Vb).

Treatment	Ratio H/Vb	LSD α 0,05 = 0.24
P1	1.32	a
P2	1.25	ab
P3	1.14	ab
P4	1.11	ab
P5	1.06	b

Source : Own Study

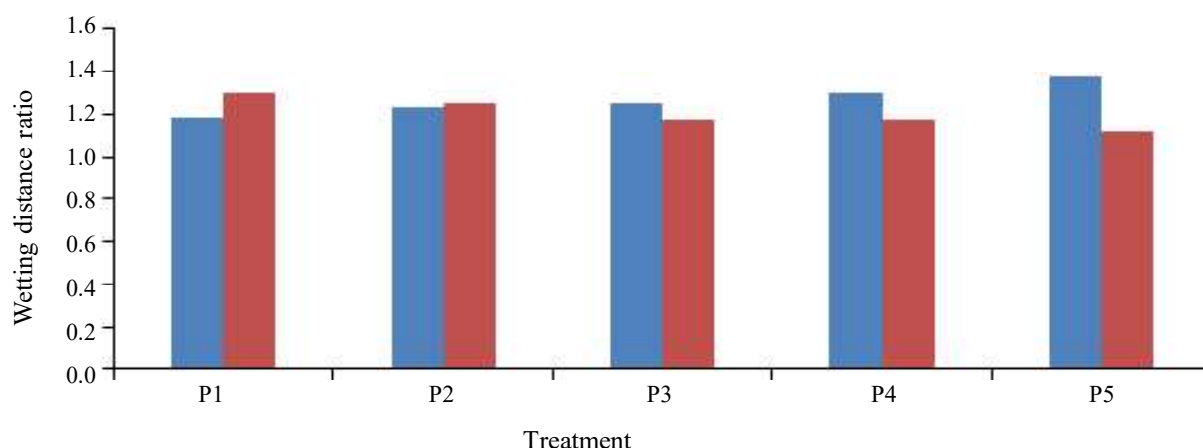


Figure 4. Ratio H/V_a and H/V_b for porous ceramic emitter on each clay and sand composition treatment. ■: H/V_a, ■: H/V_b.

rather than spreading evenly in the root zone. However, an H/Vb ratio close to 1 is still considered acceptable. Across all five tested clay-to-sand compositions, the H/Vb ratio remained ≥ 1 (Table 2) (Ma et al., 2024). This suggests that, under all treatments, water movement remained within the acceptable range.

CONCLUSIONS

The soil fraction significantly affected emitter quality. The clay-sand mixture used to produce

porous ceramic emitters influenced horizontal wetting (H) and vertical wetting (V) below the dripline, as well as the wetting ratio beneath the dripline (H/Vb). The emitter with the best sand composition (P5) shows the longest horizontal wetting distance, measuring 13.95 cm, 10.52 cm, and 13.21 cm above and below the dripline, respectively. Nonetheless, it has the lowest ratio of horizontal wetting distance to wetting distance beneath the dripline (H/Vb), measured at 1.06. Increasing sand content affects only the dripline (H/Vb). The simulation findings indicate that all

treatments have a horizontal-to-vertical wetting ratio below the dripline of ≈ 1.0 , which is a criterion for evaluating an effective wetting pattern. Porous ceramics with a composition of 1 part clay and 1.5 parts sand (P5) showed the best moisture distribution characteristics horizontally, vertically, and in the horizontal-to-vertical ratio.

The horizontal drip distance results indicate that all types of porous ceramic emitters are suitable for drip irrigation systems. However, in field applications, adjust emitter discharge, irrigation operation duration, and drip path depth according to soil type and plant water needs. After irrigation, the dripline must remain filled with water to prevent fine soil particles from hardening around the emitter. Porous ceramic with a composition of 1.5 parts sand and 1.5 parts clay (P5) exhibits the lowest compressive strength. Therefore, it is necessary to analyze the mechanical aspects and manufacturing methods to enhance its compressive strength.

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