https://doi.org/10.48196/020.02.2024.05

Submitted: October 8, 2024
Received in final revised form: December 19, 2024
Accepted: December 29, 2024

Hydraulic Performance Evaluation of Low-Cost Gravity-Fed Drip Irrigation Systems Under Falling Head Conditions

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ABSTRACT

Gravity-fed drip irrigation systems offer a cost-effective alternative to conventional systems fitted with pumps, thus making the technology accessible to small-scale farmers. However, these systems rely solely on gravitational pressure, raising concerns about their ability to maintain uniform water distribution which is a key factor for efficient irrigation and crop yield consistency. With limited studies on the performance of gravity-fed drip kits available in the Philippines, this study evaluated the hydraulic performance of two locally available drip kits, Drip Kit A and Drip Kit B, under falling head conditions to simulate actual field scenarios where the water level in the tank decreases as the water drains during operation. A 3.5 m tank platform height was utilized for practicality, with water heads ranging from 4.3 m to 3.7 m in 0.2 m increments which were constrained by the collection cups' volume capacity. Results showed a decline in emitter discharge rates as the operating head fell, where Drip Kit A exhibited slightly higher discharge rates (0.53 to 0.57 L/h) compared to Drip Kit B (0.52 to 0.54 L/h). Both kits exhibited excellent water distribution uniformity, with coefficient of uniformity (CU), emission uniformity (EU), and coefficient of variation (CV) ranging from 91.89% to 96.02%, 84.13% to 92.19%, and 0.08 to 0.15, respectively. Statistical analysis revealed no significant effect (α=5%) of the varying operating heads on CU, EU, and CV, indicating that water distribution uniformity was unaffected by a 0.2 m falling head difference and a total head difference of 0.6 m across trials. It is recommended that the operation of the Drip Kit A and B on a leveled terrain shall focus on managing emitter discharge rates to achieve the appropriate irrigation application time depending on the crop planted.

Keywords: *gravity drip irrigation, water distribution uniformity, coefficient of uniformity, emission uniformity, falling head*

INTRODUCTION

Drip irrigation is widely regarded as the most water-efficient irrigation method (Keshtgar, 2012; Riza et al, 2016). Its adoption has grown in areas with limited or expensive water supplies due to its ability to optimize water use by delivering water directly or close to the root zone, thus wetting only the soil required for plant growth. This distinguishes it from surface and sprinkler irrigation which wet the entire soil profile. Overall, under appropriate conditions and with effective management, drip irrigation maximizes efficiency and crop productivity.

A drip irrigation system delivers water or solutions (such as nutrients) to the surface or sub-surface of the plant's root zone using a network of pipe and tubing (Zaccaria and Bali, 2024). The components of a drip irrigation system are usually made up of plastic (like PE and HDPE) that include the mainlines, submains, manifolds, headers, and lateral lines with emission devices (emitters). Each emitter should produce a controlled and uniform stream of water or solutions (Zaccaria and Bali, 2024). With drip irrigation systems, farmers achieve optimum plant growth, yield, and market-desired production quality because of the high level of control of water and nutrient applications (Zaccaria and Bali, 2024).

Despite its benefits, the widespread adoption of drip irrigation has been limited due to high initial and operating costs (Singh et al., 2009). To address this, gravity-fed drip irrigation systems have been developed as a low-cost alternative, making the technology more accessible to small-scale farmers. These systems typically consist of components in a bundled kit so that farmers can conveniently assemble a complete drip system that has already been appropriately sized for their plot. Additionally, these systems utilize elevated water tanks of considerable height to generate the pressure required for operation through gravity, as the name implies, hence eliminating the need for expensive pumping units. As a result, gravity-fed drip kits are portable, affordable, and well-suited for marginal farmers with small landholdings.

Since gravity-fed systems rely solely on gravitational pressure, concerns arise about their ability to maintain uniform water distribution—a critical factor for efficient irrigation and consistent crop yields. Poor distribution uniformity is often linked to reduced crop performance (Mistry et al. 2017; Wu, 1997; Bhatnagar and Srivastava, 2003) and can be influenced by factors such as pressure variations due to elevation differences (Mizyed and Kruse, 1989; Mashandudze et al. 2015), manufacturing imperfections among emitters (Detomini et al., 2009), occurrence of emitter clogging (Barragan et al, 2006; Bralts et al, 1981; Almajeed and Alabas, 2013), friction and minor losses along the lines (Ella et al., 2009), and effect of land slope (Ella et al., 2009; Patle, 2024). Moreover, many gravity-fed drip kits lack rigorous performance evaluations (Huang, 2012), specifically the kits available in the local market.

To address this gap, Martinez et al. (2022) assessed the hydraulic performance of two gravity-fed drip kits available in the Philippines under constant head conditions. Their findings indicated that tank platform height had no significant impact on water distribution uniformity [coefficient of uniformity (CU), emission uniformity (EU), and coefficient of variation (CV)], while the discharge rate varied with hydraulic head. However, constant head conditions do not replicate real field practices in drip irrigation. In actual operation, the tanks drain progressively, where the water level inside the tank is let to descend without refilling during the irrigation (falling head condition).

Thus, this study evaluated the hydraulic performance of two low-cost gravity-fed drip irrigation kits available in the Philippines under falling head conditions, specifically focusing on the emitter discharge and water distribution uniformity. The results can be used as reference by local farmers for the design and operation of gravity-fed drip irrigation system.

MATERIALS AND METHODS

Experimental Layout and Sampling Procedure

The experiment utilized two drip irrigation kits sourced from different manufacturers and local suppliers, designated as Drip Kit A and Drip Kit B.

It should be noted that the drip kits used were the same drip kits utilized in the study of Martinez et al. (2022). Both kits are designed to irrigate a 200 m^2 corn plot and feature a 10-meter submain line connected to 14 lateral lines that are 20 m long. A 1-m^3 intermediate bulk container (IBC) tank served as the water reservoir and was elevated on a 3.5-meter-high platform. This elevation was selected based on practical and economic considerations for actual field operations.

Each drip irrigation kit was installed using an end-feed layout as illustrated in **Figure 1**. It was equipped with a screen filter installed immediately after the PVC ball valve which turns controls water flow from the tank to the linear low-density polyethylene (LDPE) submain line. The filters were essential for preventing clogging in the emitters, especially since emitters have small orifices designed to produce water drips. From the submain line, water was directed into non-pressure compensating thin-walled drip lateral lines spaced 0.75 meters apart. These lateral lines were embedded with cascade labyrinth emitters rated at 1.0 L/h that are spaced 0.30 meters apart. The spacing between the lateral lines and emitters was intended to match the corn's plant spacing requirement. To ensure accurate testing, all lines (both submain and laterals) were leveled to maintain a 0% gradient to eliminate any slope effects on the system's performance. More detailed information regarding the specifications of the drip kits is summarized in **Table 1**.

A sampling of 308 emitters out of 926 total emitters in the setup were selected for the testing. The location of each sampling emitter was identified according to its lateral line and position in the lateral line. The lateral lines are labeled with numbers 1 to 14, whereas the positions of the sampling emitters on the lateral lines are labeled with letters A to V, as shown in **Figure 1**.

Given the substantial number of data to be gathered, gravimetric method was employed to determine the discharge rate of each sampling emitter. Collecting the water discharge during the trials was done using pre-weighed 300 mL melamine cups. Due to the limited volume capacity of the cups, a falling head difference of 0.2 m was selected. Accordingly, the tank water levels were marked at 3.7 m, 3.9 m, 4.1 m, and 4.3 m to support the three falling head setups tested: (1) 4.3 m to 4.1 m, (2) 4.1 m to 3.9 m, and (3) 3.9 m to 3.7 m. For each falling operating head setup, three (3) trials of emitter discharge measurements were conducted. The total time for the water to descend in the tank according to the falling operating head setup being tested was also recorded. After each trial, the mass of each cup containing its collected water from the sampling emitter was measured using a digital weighing scale. Assuming that the density of water is 1.0 g/cm3, the emitter discharge rate was computed using Equation 1:

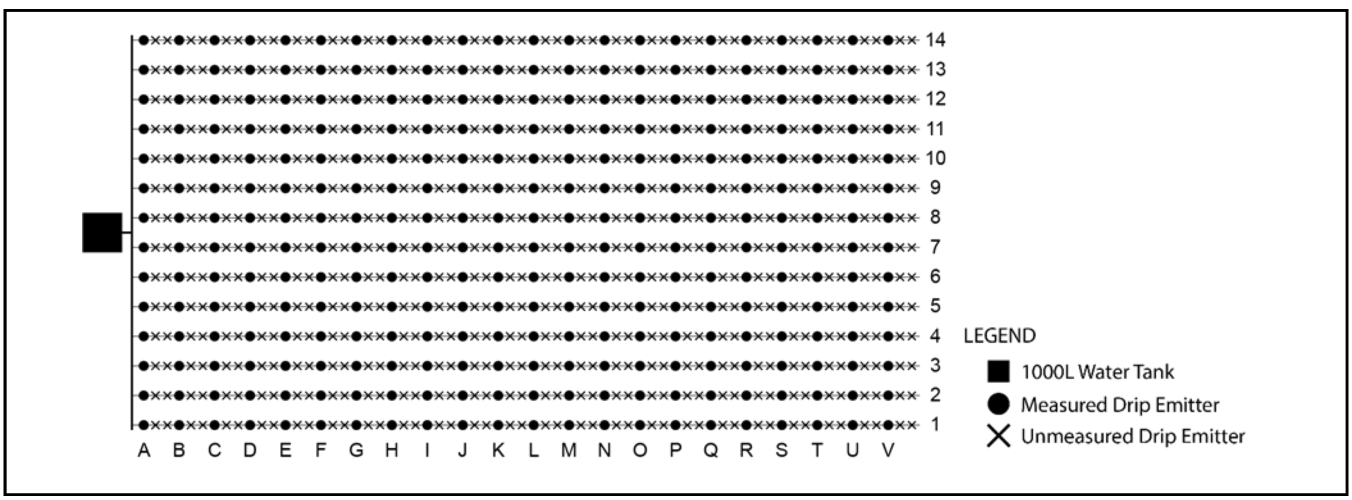

Figure 1. Experimental end-feed drip irrigation layout showing the sampling emitters in the falling head performance testing (Adopted from Martinez et al., 2022).

Table 1. Specifications of the drip irrigation kits A and B used in the study.

COMPONENTS	Drip Kit A	Drip Kit B
Main and submain line	LLDPE hose, 32-mm outer diameter, 2-mm wall thickness	LLDPE hose, 25-mm outer diameter, 2.5-mm wall thickness
Lateral line and emitter	Non-pressure compensating thin-walled drip line with cascade labyrinth emitter, 30-cm spacing, 17-mm nominal diameter, 1.0 L/h	Non-pressure compensating thin-walled drip line with cascade labyrinth emitter, 30-cm spacing, 17-mm nominal diameter, 1.0 L/h
Valve	32-mm PVC ball valve, female/female	25-mm PVC ball valve, female/female
Screen filter	130 microns	125 microns
Main-submain line fittings	32-mm compression fittings: 1 pc equal tee 1 pc female adapter 1 pc male adapter 2 pcs equal elbow 2 pcs end cap	25-mm compression fittings: 1 pc equal tee 1 pc female adapter 1 pc male adapter 2 pcs equal elbow 2 pcs end cap
Lateral line fittings	16-mm PE: 14 pcs start connector 14 pcs end line	16-mm PE: 14 pcs start connector 14 pcs end line
Package Price[a]	$200.00	$140.00

[a] *The drip kits contain additional parts, but the approximate price will not significantly vary. The package does not include the IBC tank and tank stand.*

Source: (Adopted from Martinez et al., 2022)

$$q = \frac{3}{50}\frac{m_t - m_c}{t} \qquad \textbf{Equation 1}$$

where,

q is the individual sampling emitter discharge, L/h
m_t is the total mass of cup and collected water discharge, g
m_c is the mass of cup, g
t is the time, min

The resulting emitter discharge rate values were then analyzed and used to generate mathematical models to describe the relationship of the falling operating head to the average emitter discharge rate for Drip Kit A and Drip Kit B. Additionally, the emitter discharge rate variation along the lateral line for both drip irrigation kits was also examined.

Water Distribution Uniformity and Statistical Analysis

As water distribution uniformity is vital for efficient irrigation and consistent crop yields, the study investigated the following uniformity parameters:

1. Coefficient of uniformity (CU). The most widely used CU is the Christiansen's uniformity coefficient which measures the ability of the drip irrigation system to distribute the water uniformly in the whole field. It is classified based on **Table 2** and is given by the formula (Christiansen, 1942):

$$CU = \left(1 - \frac{\sum_{i=1}^{n}|q_i - M|}{\sum_{i=1}^{n} q}\right) \times 100 \qquad \textbf{Equation 2}$$

where,

CU is the coefficient of uniformity, %
n is the number of observed emitter discharge rate values
q_i is the individual emitter discharge rate, L/h
M is the average of emitter discharge rate values = $\frac{1}{n}\sum_{i=1}^{n} q_i$, L/h

Table 2. Drip irrigation system uniformity classification based on uniformity coefficient.

UNIFORMITY COEFFICIENT, CU (%)	CLASSIFICATION
> 90	Excellent
90 - 80	Good
80 - 70	Fair
70 - 60	Poor
< 60	Unacceptable

Source: ASAE Standards EP458.

2. Emission Uniformity (EU). This parameter is also known as distribution uniformity and measures the uniformity of the emitters belonging to the lowest quarter with the least discharge. It is classified based on **Table 3** and is expressed by (Ortega et al. 2002; Keller and Bliesner, 1990):

$$EU = \left(\frac{q_{LQ}}{M}\right) \times 100 \qquad \textbf{Equation 2}$$

where,
EU is the emission uniformity, %
q_{LQ} is the average of the lowest quarter of the emitter discharge rate values, L/h
M is the average of emitter discharge rate values , L/h

Table 3. Drip irrigation system uniformity classification based on emission uniformity.[a]

EMISSION UNIFORMITY, EU (%) [b]	CLASSIFICATION
94 - 100	Excellent
81 - 87	Good
65 - 75	Fair
56 - 62	Poor
< 50	Unacceptable

[a] *Source: ASAE Standards EP458.*
[b] *Note: The discontinuities in the EU scale are to cater for the 95% confidence limits of the measures, and these tend to be high for low uniformities.*

3. Coefficient of Variation (CV). This parameter is also known as the manufacturer's coefficient of variation which measures the manufacturing variation of emitters. It is classified based on **Table 4** and is given by the following formula (Al-Amound, 1995; Burt and Styles, 2007):

$$CV = \frac{\sigma}{M} \qquad \textbf{Equation 2}$$

where,
CV is the coefficient of variation
σ is the standard deviation of the emitter discharge rates, L/h
M is the average of emitter discharge rate values , L/h

Table 4. Drip irrigation system classification based on the coefficient of variation.

COEFFICIENT OF VARIATION, CV	CLASSIFICATION
<0.1	Excellent
0.1 – 0.2	Very Good
0.2 – 0.3	Acceptable
0.3 – 0.4	Low
>0.4	Unacceptable

Sources: Bralts and Kesner, 1983; Keller and Bliesner, 1990; ASAE, 1984

Calculated CU, EU, and CV values for both drip kits were then subjected to the Shapiro-Wilk test of normality and the Kruskal-Wallis H test with a 95% confidence level to check whether these values significantly differ on operating heads.

RESULTS AND DISCUSSION

Head-Discharge Relationship of Emitters

A box plot was used to visualize the emitter discharge sampling results, as illustrated in **Figure 2.** The data suggests a lack of symmetry in the distribution of emitter discharges, hence emphasizing the variations in discharge rates. Therefore, this observation stresses the necessity of evaluating the uniformity of the system to analyze the hydraulic performance of the drip kits.

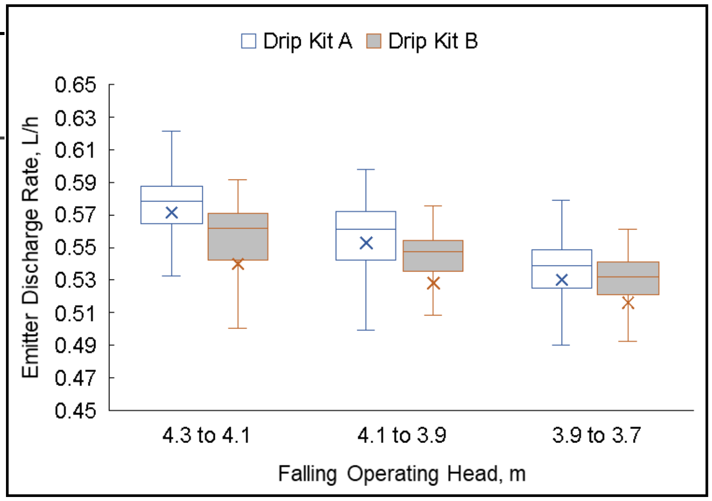

Figure 2. Average emitter discharges of Drip Kits A and B at different falling head conditions.

As shown in **Table 5**, the emitter discharges for Drip Kit A were consistently higher than those for Drip Kit B across all tested falling head settings. The highest average discharge was recorded for Drip Kit A, with 0.57 L/h at a head of 4.3 to 4.1 m, while the lowest was observed in Drip Kit B, with 0.52 L/h at a head of 3.9 to 3.7 m. Overall, Drip Kit B exhibited lower discharge values across all trials. This may be attributed to manufacturing inconsistencies or clogging given that the system was newly installed for the sole purpose of this study. The emitter discharge values were within the values obtained during the constant head test (Martinez, et al, 2022). From the constant head test, the average emitter discharge of Drip Kit A was 0.56 L/h at 3.5m head,

Table 5. Minimum, average, and maximum emitter discharge values under falling operating heads for the drip kits.

HEAD, m	EMITTER DISCHARGE ACROSS THE TRIALS, L/h					
	Drip Kit A			Drip Kit B		
	Min	Ave	Max	Min	Ave	Max
4.3 to 4.1	0.43	0.57	0.62	0.04	0.54	0.59
4.1 to 3.9	0.34	0.55	0.60	0.06	0.53	0.58
3.9 to 3.7	0.36	0.53	0.59	0.07	0.52	0.58

0.58 L/h at 4.0m and 0.59 L/h at 4.5m (Martinez, et al, 2022). While the average emitter discharge of Drip Kit B was 0.52 L/h at 3.5m head, 0.56 L/h at 4.0m and 0.59 L/h at 4.5m (Martinez, et al, 2022).

Despite some fluctuations in discharge values, the average values evidently indicate that emitter discharge rates are strongly influenced by the operating head. The higher operating heads corresponded to increased discharge rates, which is consistent with the fundamental principles of hydraulics in drip irrigation systems (**Figure 3**).

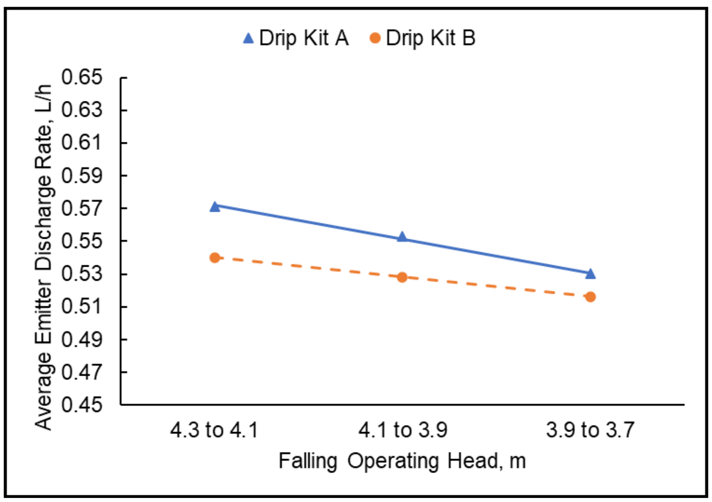

Figure 3. Relationship between average emitter discharge and falling operating head for Drip kits A and B.

Although there is a standard head-discharge relationship for drip irrigation, the results observed in this study deviate from this expected pattern. As a result, linear regression analysis was applied to empirically describe the relationship between average emitter discharge and falling operating head for each drip kit (**Table 6**). However, it is important to note that the linear regression models generated, as presented in **Table 6**, are applicable only to comparable setups and may not be applicable to other operating conditions. Emitter flow variation of 10–20%, produces only a few percent change in uniformity (Wu, 1997).

The emitters are rated at 1.0 L/h by the manufacturers; however, none of the falling head setups reached this discharge rate. According to the regression models presented in **Table 6**, a tank height of at least 20 m for Drip Kit A and 39 m for Drip Kit B would be necessary to achieve the 1.0 L/h discharge rate, which is clearly impractical and costly for a 200-m³ corn plot. As stated before, these linear regression models should be interpreted with caution as their applicability may be limited to tank elevations used in this study.

Table 6. Linear regression models for average emitter discharge as a function of falling operating head for the drip kits.

DRIP KIT	LINEAR REGRESSION MODEL	R^2
A	$q = -0.0206H + 0.5927$	0.99
B	$q = -0.0119H + 0.5519$	0.99

Note: q = average emitter discharge (L/h); H = falling operating pressure head (m)

Emitter Discharge Variation in Lateral Lines

The average emitter discharges along the laterals were plotted against the distance for each operating head of the two drip kits, as shown in **Figure 4**. Due to friction and minor losses along the lateral lines, it is expected that emitter discharge would decrease as the distance from the start of the lateral line increases, i.e. a negative slope. However, it is unusual to observe a positive trend, as exhibited by Drip Kit A in the 4.3 to 4.1 m falling head setting. This could be attributed to the undulations formed by the lateral lines during operation due to the weight of the water. Overall, the distance of the emitters was found to significantly influence the discharge as demonstrated by the linear regression models summarized in **Table 7**. On the other hand, the result of the constant head test (Martinez, et al, 2022), showed a relatively defined trend for emitter discharge.

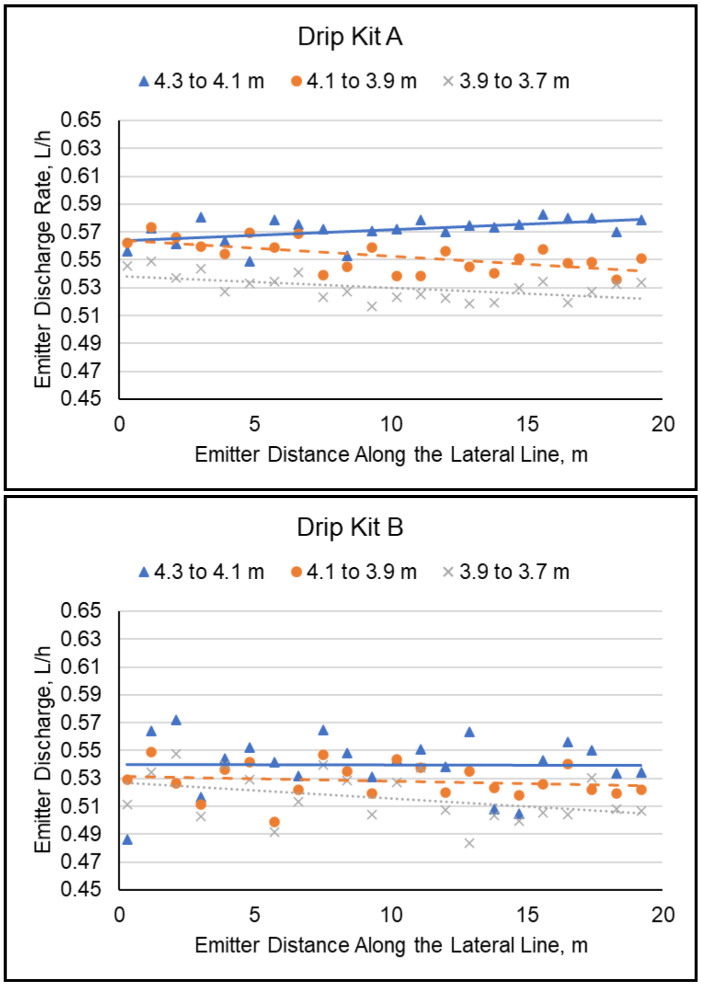

Figure 4. Emitter discharge variation of the drip kits along the lateral at different operating heads.

Water Distribution Uniformity of the System

Table 8 presents the computed values for Christiansen's coefficient of uniformity (CU), emission uniformity (EU), and coefficient of variation (CV) for the two locally available gravity-fed drip kits used in the study. Generally, EU have lower values compared to CU, as EU is based on the lowest quarter of emitter discharges, i.e. least efficient emitters. Drip Kit A exhibited better water distribution uniformity with CU values ranging from 96.02% to 94.56%, EU from 89.53% to 89.67%, and CV from 0.08 to 0.09. On the other hand, Drip Kit B (**Table 9**) yielded better water distribution uniformity during the constant head test (Martinez, et al, 2022). In a study by Huang (2012), the first drip kit tested has a CU of 66.8% while the second drip kit has a CU of 55.6%. On the other hand, in the study of Ella et al. (2009), the maximum UC of 71% and maximum EU of 53.5% occur at a head of 3.0 m when the drip system is laid on a level surface. Heads lower or higher than 3.0 m yielded slightly lower UC and EU (Ella et al. 2009). Based on the classifications provided in **Tables 2** and **3**, both drip kits A and B showed excellent overall performance in terms of CU and good performance in the EU. Drip Kit A performed excellently in terms of CV, while Drip Kit B demonstrated only good performance. The emitter flow variation from 10% to 20% (which is lower in this study) in hydraulic design will reduce spatial uniformity of only about 8% (from 93% to 85%) when the emitter spacing is designed as half of the wetting diameter in the field (Wu, 1997).

The higher CU and EU of Drip Kit A suggest more consistent emitter discharge across the system. The CV values suggest that Drip Kit A provides more consistent emitter discharge as compared to Drip Kit B. This means that Drip Kit A has lesser manufacturing variations. With lesser variations, the crops in the plot fitted with the said drip kit will be ensured that their crop water requirements will be met consistently, which will result in consistent, if not higher, crop yields.

Table 5. Minimum, average, and maximum emitter discharge values under falling operating heads for the drip kits.

HEAD, m	EMITTER DISCHARGE ACROSS THE TRIALS, L/h			
	Drip Kit A		Drip Kit B	
	Linear Regression Equation	R^2	Linear Regression Equation	R^2
4.3 to 4.1	$Y = 8.02\times10^{-4} X + 0.56$	0.26	$Y = -4.22\times10^{-5} X + 0.54$	0.00
4.1 to 3.9	$Y = -1.18\times10^{-4} X + 0.56$	0.38	$Y = -3.49\times10^{-4} X + 0.53$	0.03
3.9 to 3.7	$Y = -8.43\times10^{-4} X + 0.54$	0.29	$Y = -1.20\times10^{-3} X + 0.53$	0.15

Note: Y = individual emitter discharge rate, L/h
X = distance of the emitter along the lateral line from the submain line, m

These findings highlight that, while both systems exhibit positive performance, Drip Kit A generally outperforms Drip Kit B, particularly in terms of emitter discharge and uniformity. However, it should be noted that further analysis of operational and environmental factors may be necessary to fully optimize performance for specific agricultural applications as the study focused on drip kits specifically designed for 200-m^2 corn production.

Using the Shapiro-Wilk test of normality, it was found that the data gathered for both drip kits did not follow the normal distribution. Hence, to validate whether the CU, EU, and CV values significantly differ on operating heads, the Kruskal-Wallis H test was employed with a 95% confidence level. The statistical test showed that CU ($H(2) = 3.47$, $p = .18$), EU ($H(2) = 2.76$, $p = .25$), and CV ($H(2) = 1.42$, $p = .49$) of Drip Kit A are not significantly different for the operating falling heads, i.e., changing the operating heads will not influence the CU, EU, and CV values for Drip Kit A. Likewise, CU ($H(2) = 1.69$, $p = .43$), EU ($H(2) = 1.07$, $p = .59$), CV ($H(2) = 2.49$, $p = .29$) of Drip Kit B also showed similar results.

The statistical results suggest that the three falling operating heads tested (each with a 0.2 m difference) do not significantly impact water distribution uniformity for a leveled 200-m² plot. This finding indicates that uniformity may not be a primary concern under comparable conditions. Instead, the focus should shift to managing emitter discharge rates which directly affect irrigation volume and application duration.

Emitter discharge rates are influenced by the operating head, hence adjusting the tank elevation can help achieve the desired discharge. However, larger falling head differences than those evaluated in this study might result in reduced water distribution uniformity, thereby potentially affecting the system's performance and crop yield consistency. Furthermore, increasing tank elevation beyond practical limits can introduce challenges, such as difficulties in refilling the tanks in areas with insufficient water supply pressure and additional costs for constructing higher tank platform stands.

Ultimately, the design and implementation of gravity-fed drip irrigation systems must be tailored to the specific crop and site conditions. Practical and economic considerations are critical to ensuring these systems remain accessible to small-scale farmers.

Table 8. Coefficient of uniformity, emission uniformity, and coefficient of variation at falling operating heads for the Drip Kits A and B.

HEAD, m	Drip Kit A			Drip Kit B		
	CU, %	EU, %	CV	CU, %	EU, %	CV
4.3 to 4.1	94.56	89.67	0.09	91.89	84.13	0.15
4.1 to 3.9	96.02	92.19	0.08	92.47	85.58	0.15
3.9 to 3.7	94.98	89.53	0.09	93.23	86.71	0.14
Classification	Excellent	Good	Excellent	Excellent	Good	Very Good

Table 9. Coefficient of uniformity, emission uniformity, and coefficient of variation at constant operating heads for the Drip Kits A and B.

HEAD, m	Drip Kit A			Drip Kit B		
	CU, %	EU, %	CV	CU, %	EU, %	CV
4.5	97.7	96.3	0.04	98.5	97.7	0.03
4.0	97.6	96.3	0.04	98.3	97.4	0.03
3.5	97.5	95.9	0.04	98.4	97.5	0.03
Classification	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent

CONCLUSION

The average emitter discharge values evidently indicate are strongly influenced by the operating head. The higher operating heads corresponded to increased discharge rates, which is consistent with the fundamental principles of hydraulics. The study also revealed that a tank outlet elevation of 3.5 m failed to achieve the manufacturer's specified emitter discharge rate of 1.0 L/h. This will result in slower water delivery to the plant roots and extended irrigation application times. Both Drip Kit A and B have very good water distribution uniformity in terms of CU and EU. But overall, Drip Kit A has better hydraulic performance at varying head conditions due to relatively higher emitter discharge and lower CV.

RECOMMENDATION

Based on the results of this study, a head difference of 0.2 m did not significantly affect the water distribution uniformity of gravity-fed drip irrigation systems on flat terrain. This limitation is attributed to the volume capacity of the collection cups used which constrained the potential head difference. To address this, the use of larger collecting containers is recommended to accommodate higher emitter discharge rates and greater head differences in future evaluations. To facilitate the broader adoption of low-cost gravity-fed drip irrigation systems, further research is advised on drip kits with varying emitter specifications and lateral lengths installed on fields with diverse slope topographies. Additionally, as drip kits are expected to be used over extended periods, longitudinal studies are crucial to compare their hydraulic performance at the time of installation versus after prolonged use, where emitter clogging and material degradation are accounted for. Since varying head conditions did not affect water distribution uniformity, it is recommended that the operation of the Drip Kit A and B on a leveled terrain shall focus on managing emitter discharge rates to achieve the appropriate irrigation application time depending on the crop planted.

ACKNOWLEDGEMENT

This study was supported by the Commission on Higher Education – Philippine-California Advanced Research Institutes (CHED-PCARI) through the PCARI-WiSEIr Project titled, "Development of wireless sensor network-based water information system for efficient irrigation water management in the Philippines."

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