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HYDRAULIC PERFORMANCE EVALUATION OF A LOW-PRESSURE GRAVITY-FED DRIP IRRIGATION SYSTEM FOR OIL PALM SEEDLINGS

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ABSTRACT

Gravity-fed drip irrigation system offer a cost-effective and energy-efficient irrigation alternative, particularly suitable for smallholder farmers with limited access to conventional pump-driven irrigation systems. However, their reliance on gravitational head raises concerns over their ability to sustain uniform water application, a critical factor influencing irrigation performance, water-use efficiency, and crop productivity. A nursery-scale experiment was conducted to evaluate the hydraulic performance of a pre-installed low-pressure gravity-fed drip irrigation system used for irrigating oil palm seedlings. The system consisted of a 50 - L elevated storage drum connected to a drip irrigation system installed over an experimental area of 22.5 m². Hydraulic performance was assessed using average emitter discharge, coefficient of variation (CV), emission uniformity (EU), statistical uniformity (Us), and Christiansen uniformity coefficient (CU). The average emitter discharge was 0.474 ± 0.049 L h⁻¹, while the CV, EU, Us, and CU averaged 0.037 ± 0.009, 96.14 ± 0.67%, 96.31 ± 0.91%, and 97.26 ± 0.72%, respectively. These values indicate excellent hydraulic performance and highly uniform water distribution throughout the irrigation network. Despite a gradual decline in hydraulic head resulting from water depletion in the storage tank, the system maintained stable discharge and uniformity, with only minor variations observed among inlet, intermediate, and terminal emitters. The results demonstrate that low-pressure gravity-fed drip irrigation can provide uniform water application. The system represents a practical and economically viable irrigation approach that can improve water use efficiency and support the sustainable production of oil palm nursery seedlings, particularly under smallholder farming conditions.

Key words: oil palm seedlings; hydraulic parameters; micro-irrigation; emission uniformity; water use efficiency

INTRODUCTION

Agriculture is the largest consumer of global freshwater resources, with irrigated crop production, livestock, fisheries, aquaculture, and forestry collectively accounting for about 70% of total freshwater withdrawals. This dependence is even more pronounced in majority of the least developed countries where agriculture constitutes 90% of fresh water use, with irrigation alone contributing approximately two-thirds of total agricultural water demands (IFAD, 2021; UNESCO, 2024). The excessive use of water resources is increasingly considered unsustainable and poses a direct challenge to Sustainable Development Goal 6 (SDG 6) of the United Nations, which seeks to ensure availability and sustainable management of water and sanitation for all (Sadoff *et. al.,* 2020). In this context, the adoption of efficient irrigation technologies is essential for advancing progress toward SDG 6, by improving water use efficiency in agriculture and supporting the sustainable management of fresh water resources.

Irrigation systems provide controlled and timely water supply to crops, thereby improving productivity under water-limited conditions (Lamm *et al.*, 2007; Obalum and Azuka, 2021). Micro-irrigation, a critical precision irrigation technology, is widely employed globally due to its ability to deliver nutrient-rich water directly to the crop root zone in a controlled and efficient manner. Drip irrigation which is a type of micro-irrigation system has gained attention due to its ability to deliver water directly to the plant root zone with minimal evaporation and runoff losses, resulting in enhanced crop performance and water use efficiency (Obalum *et al*, 2011; Assefa *et al.*, 2018; Vaddula and Singh, 2023; Guo and Li, 2024). Low head drip irrigation systems typically operate under gravity-driven pressures of 0.5-4.0 m head, whereas conventional drip systems require 7-21 m (Ngigi *et al.*, nd; Martinez *et al.*, 2024; Sahu *et al.*, 2024). Gravity-fed systems supply the entire drip irrigation system from an overhead tank. The water is made to flow under the influence of gravity and the pressure of water in the system is related to the ground level.

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The adoption of drip irrigation technology has increased considerably in Nigeria and other developing countries because of its potential to improve irrigation efficiency, enhance crop productivity, and conserve water resource. Numerous studies have reported the benefits of drip irrigation for various crops, including onion, pepper, soybeans and vegetables under different environmental and management conditions (Adeboye *et al.*, 2015; Ezekiel *et al.*, 2016; Assefa *et al.*, 2019; Oluwagbayide *et al.*, 2020; Abegunrin *et al.*, 2023). These studies generally demonstrate improvements in water productivity, crop yield, and economic returns when compared with conventional irrigation methods. Ovie *et al.* (2013) showed that effective irrigation management enhances oil palm seedling growth, underscoring the need for efficient water delivery systems in nursery production.

In addition to agronomic evaluations, several researchers have investigated the hydraulic performance of gravity-fed drip irrigation systems operating under low-pressure conditions. (El-Mansy *et al.*, 2024) reported high emission uniformity values ranging from 90 to 97% for low-pressure drip irrigation systems designed for smallholder farming, demonstrating their ability to provide fairly uniform water application under varying operating conditions. Similarly, Martinez *et al.* (2024) evaluated two locally available drip irrigation kits under falling-head conditions and found that both systems exhibited excellent hydraulic performance, with coefficient of uniformity (CU) values ranging from 91.89 to 96.02%, emission uniformity (EU) values from 84.13 to 92.19%, and coefficient of variation (CV) values between 0.08 and 0.15. These performance indicators fall within acceptable standards for drip irrigation systems and suggest that well-designed gravity-fed systems can achieve satisfactory water distribution despite operating under low pressure.

Oil palm (*Elaeis guineensis*) is a major economic crop in Nigeria, contributing significantly to national agricultural output, rural incomes, and industrial development (Okolo *et al*., 2019; FAO, 2024; Ugwu *et al*., 2024). According to Statista (2020), Nigeria ranks as the fifth largest producer of palm oil globally, with an annual production of 1.0 million metric tonnes (Mt). This is considerably lower than that of Indonesia and Malaysia which produce about 42.5 and 18.5 million Mt, respectively. The nursery stage is critical to successful plantation establishment, as seedling vigour largely determines subsequent field performance and yield potential (Corley and Tinker, 2016). Successful oil palm production is closely linked with proper nursery management, as healthy seedlings are essential for field establishment and long-term yield performance. Oil palm seedlings require adequate and uniform water supply for proper growth, development of leaf, and root formation, making efficient water management in the nursery critical (Carr, 2011; Corley and Tinker, 2016).

Despite the increasing use of drip irrigation as a water efficient technology, limited information exists on the hydraulic performance of low-pressure gravity fed drip irrigation systems for oil palm nursery seedlings, particularly under Nigerian conditions. Evaluating the performance of such systems is important because they offer a low-cost and water efficient irrigation option for small holder farmers. Therefore, this study aimed to evaluate the hydraulic performance of a simple low-pressure gravity-fed drip irrigation system and its suitability for nursery water management in oil palm seedling production.

MATERIALS AND METHODS

Study Area

This study was carried out at the Nigerian Institute for Oil palm Research (NIFOR) Main Station, Benin, Edo State, Nigeria. The study area is characterised by a tropical rainforest climate with a bi-modal rainfall pattern. It is located between 6º22.66′ N to 6º22.60′ N and 5º22.41′ E to 5º22.87′ E. The annual rainfall ranges from 1500 mm to 2500 mm, with a mean value of about 1700 mm during the wet season, which extends from March to October. Temperature in the area is relatively uniform throughout the year, with an annual average of 31ºC and minimal seasonal variation. The soils are classified into four major soil series namely Alagba, Orlu, Ahiara and Kulfo which are Rhodic Paleudult and Typic Dystropet according to USDA Soil Taxonomy classification (Ogunkunle, 1983). The location map of the study area is shown in Figure 1.

Description of the Drip Irrigation System

The study utilised a pre-installed low-pressure gravity-fed drip irrigation system for irrigating oil palm nursery seedlings. The system was installed on an experimental area measuring 7.5 m × 3.0 m, corresponding to a total irrigated area of 22.5 m². Water was supplied from a 50 L cylindrical storage drum elevated 1.5 m above ground level, providing the operating head required for gravity driven flow. The irrigation network consisted of a mainline, sub-main and lateral lines fitted with inline emitters for water application to oil palm seedlings. The main line and sub main comprised of polyvinyl chloride (PVC) pipes with nominal diameters of 1″ and ¾″, respectively. Drip tapes (16 mm) with in-line emitters spaced at 0.5 m intervals were used as laterals. Control valves were installed at the junction of the sub-main and laterals to regulate water flow to each lateral line. Four replicate irrigation units were installed within the experimental area. Each replicate consisted of four lateral lines, while each lateral contained four emitters. The layout of the irrigation system is presented in Figure 2.

Hydraulic Performance Evaluation of the Drip Irrigation System

Hydraulic performance evaluation of the gravity-fed drip irrigation system was conducted under actual operating conditions. The system was operated at an

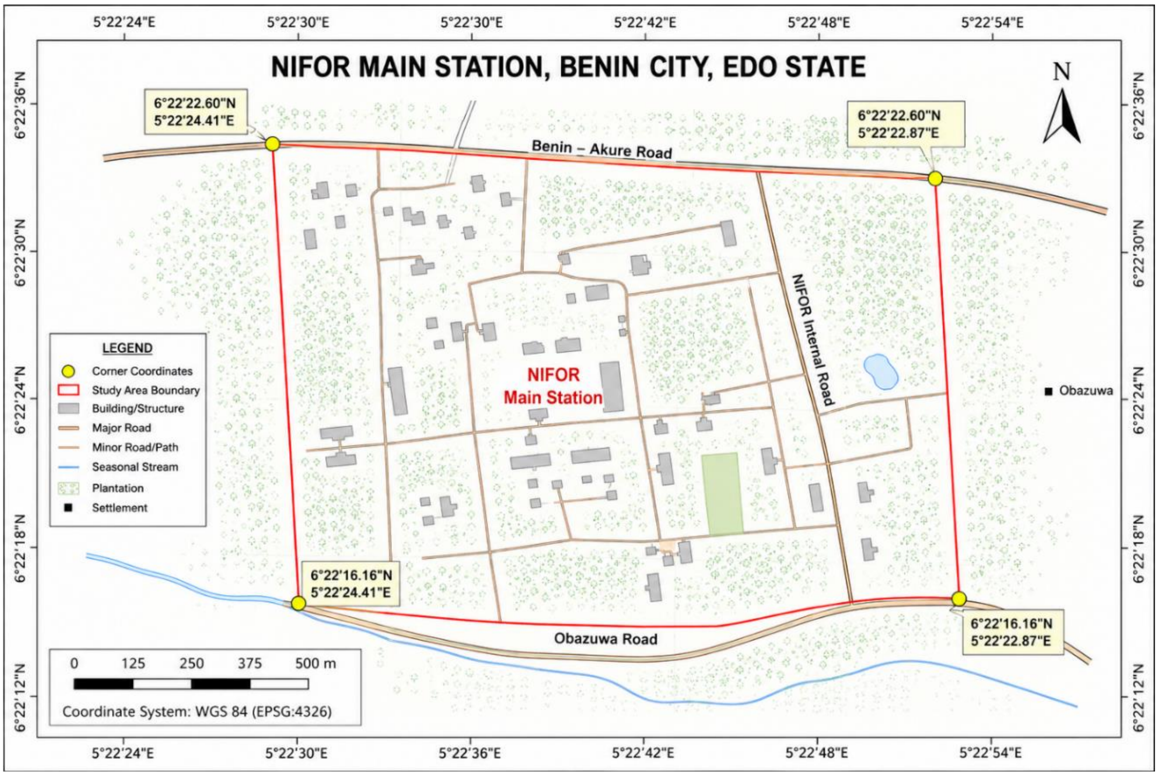

Figure 1: Location map of the study

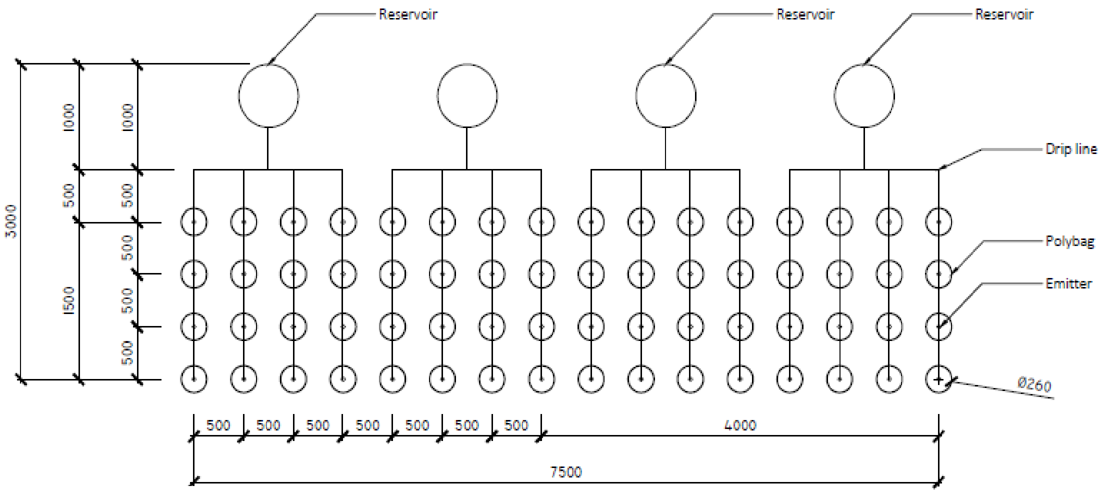

Figure 2: Layout of the experiment

initial water head of 1.5 m at the commencement of each evaluation. Emitter discharge was determined by collecting water emitted from selected emitters over a period of 60 min. The collected volume was measured using a graduated cylinder and converted to discharge rate expressed in litres per hour (L h^{-1}). To assess discharge variation along the lateral lines, emitters located at the beginning, middle, and end of each lateral were selected for measurement. Specifically, the first emitter (near the inlet), third emitter (intermediate position), and fourth emitter (terminal position) were used to represent discharge conditions along the flow path of the lateral. Since each irrigation unit consisted of four lateral lines, a total of twelve emitter discharge measurements were obtained per replicate. Across the four replicated irrigation units, forty-eight emitter observations were recorded and used for hydraulic performance analysis.

Water was supplied from the elevated storage tank without replenishment during the evaluation period. Consequently, the available pressure head gradually decreased with time, giving a falling-head operating condition throughout the test. Thereafter, measured emitter discharge data were used to determine key hydraulic performance indicators, including average emitter discharge, coefficient of variation (CV), statistical uniformity (Us), emission uniformity (EU), and Christiansen's coefficient of uniformity (CU).

Hydraulic performance parameters

The hydraulic performance of the low-pressure gravity-fed drip irrigation system was evaluated using standard hydraulic indicators derived from the measured emitter discharge data. The parameters used in the evaluation are presented below:

i. **Average emitter discharge (q_a):** Average emitter discharge represents the mean volume of water discharged by emitters per unit time. It was determined using Equation (1):

$$\frac{1}{n}\sum_{i=1}^{n} qi \quad (1);$$

where qa is the average emitter discharge (L h⁻¹), qi is the discharge of an individual emitter (L h⁻¹), and *n* is the number of emitter observations.

ii. **Coefficient of variation (CV):** The coefficient of variation (CV) is a measure of discharge variability among emitters and was calculated as the ratio of the standard deviation of emitter discharge to the mean emitter discharge, as shown in Equation 2.

$$CV = \frac{Sq}{qa} \quad (2);$$

where Sq is standard deviation of emitter flow rate and qa is the average emitter discharge (L h⁻¹). The classification of CV is as shown in Table 1.

iii. **Statistical uniformity (Us):** Statistical uniformity evaluates the uniformity of water application within the irrigation unit. This statistical uniformity was determined using Equation 3:

$$Us = 100(1 - CV) \quad (3);$$

where Us is statistical uniformity and CV is coefficient of variation. The statistical uniformity classification is presented in Table 2.

iv. **Emission uniformity (EU):** Emission uniformity (EU) expresses the relationship between the average discharge of the lowest 25% of emitters and the overall average emitter discharge. It was calculated using Equation 4:

$$Eu = 100\,\frac{\bar{q}_{25\%\,min}}{\bar{q}} \quad (4);$$

where EU is emission uniformity (%), $\bar{q}_{25\%\,min}$ is average of 25% of the lowest values of flow rate (L h⁻¹), and $\bar{q}$ is the average flow rate (L h⁻¹). The classification of EU is presented in Table 3.

v. **Christiansen Uniformity Coefficient (CU):** Christiansen's Uniformity Coefficient (CU) is widely used to evaluate the uniformity of water application in irrigation systems. It was determined using Equation 5:

$$UC = 100[1 - \frac{1}{n\,qa}\sum_{i=1}^{n}|q_i - q_a| \quad (5);$$

where *n* is number of emitters under consideration, qa is mean flow rate of the emitter (L h⁻¹), and qi is flow rate of the emitter *i* (L h⁻¹). The Christiansen uniformity coefficient is classified based on Table 4.

Table 1: Classification of uniformity based on coefficient of variation (CV)

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

Source: Keller and Bliesner, 1990

Table 2: Classification of uniformity based on statistical uniformity (Us)

Statistical uniformity (Us)	Classification
> 90	Excellent
90 – 80	Good
80 – 70	Fair
70 – 60	Poor
< 60	Unacceptable

Source: ASAE, 1996

Table 3: Classification of uniformity based on emission uniformity (EU)

% Emission uniformity (EU)	Classification
94 – 100	Excellent
81 – 87	Good
65 – 75	Fair
56 – 62	Poor
< 50	Unacceptable

Source: ASAE, 1996

Table 4: Classification of uniformity based on Christiansen's uniformity coefficient (CU)

% Uniformity coefficient (CU)	Classification
> 90	Excellent
90 – 80	Good
80 – 70	Fair
70 – 60	Poor
< 60	Unacceptable

Source: ASABE 1999 (ASABE Standards EP458)

RESULTS AND DISCUSSION

Hydraulic Performance Indicators

Table 5 presents the hydraulic performance indicators of the gravity-fed drip irrigation system obtained from the four replicated irrigation units.

The hydraulic performance indicators presented in Table 5 indicate the excellent performance of the gravity-fed drip irrigation system. Average emitter discharge ranged from 0.43 to 0.54 L h⁻¹, indicating relatively consistent water delivery across the four irrigation units. The slight variation in discharge may be attributed to minor friction losses along the laterals and inherent differences in emitter characteristics. These findings are comparable to those reported by Martinez *et al.* (2024), who observed discharge rates ranging from 0.53 to 0.57 L h⁻¹ for Drip Kit A and from 0.52 to 0.54 L h⁻¹ for Drip Kit B under low-pressure conditions.

The coefficient of variation (CV) ranged from 0.03 to 0.05, indicating very low discharge variability among emitters. According to commonly accepted classification standards, CV values below 0.10 are considered excellent and reflect high emitter performance and manufacturing consistency (Table 1). Similarly, Martinez *et al.* (2024) reported

Table 5: Hydraulic performance indicators of drip irrigation system

S/N	Parameters	Replicate 1	Replicate 2	Replicate 3	Replicate 4
1	Average emitter discharge (L h^{-1})	0.54	0.43	0.45	0.48
2	Coefficient of variation	0.03	0.05	0.04	0.04
3	% Statistical uniformity	97.38	95.17	96.46	96.24
4	% Emission uniformity	96.76	95.21	96.38	96.19
5	% Christiansen uniformity coefficient	97.92	96.30	97.70	97.13

CV values ranging from 0.08 to 0.09, which, though slightly higher than the values in the present study, also indicated satisfactory hydraulic performance. The lower CV values observed in this study suggest a high degree of discharge uniformity and minimal influence of pressure variation on emitter flow rates.

Consequently, the system exhibited high values of statistical uniformity (Us), emission uniformity (EU) and Christiansen's uniformity coefficient (CU), in the ranges of 95.17-97.38%, 95.21-96.76% and 96.30-97.92%, respectively. These values exceed the minimum thresholds generally recommended for excellent drip irrigation performance and indicate a highly uniform distribution of water throughout the system (Tables 2-4). The present findings, however, agree with those of Raphael *et al.* (2018), Olorunwa *et al.* (2019), Martinez *et al.* (2024), and Patle (2024), who also reported comparable levels of irrigation uniformity. This consistency across studies highlights the effectiveness of gravity-fed drip irrigation systems in maintaining uniform water distribution when operated.

The high uniformity indices obtained in this study can be largely attributed to the relatively short lateral length (2 m), which minimised friction losses and pressure head reductions along the drip lines. Also, the low operating pressure requirements of the emitters and the limited distance between the water source and emitters likely contributed to the maintenance of near-uniform discharge rates across the irrigation units. These results indicate that a simple gravity-fed drip irrigation system can achieve excellent hydraulic performance and water application uniformity, making it a suitable irrigation option for smallholder oil palm nursery production.

Emitter Discharge Distribution along the Laterals

The discharge characteristics of the irrigation system along the lateral line are presented in Figure 3. Discharge measurements obtained at the first, third, and terminal emitter positions were used to evaluate variation in emitter discharge along the lateral lines.

Emitter discharge showed only slight variations across the measured positions along the lateral lines with average emitter discharge values ranging from 0.467 to 0.482 L h^{-1}. The small variation suggests that the system maintained uniform hydraulic conditions along the lateral lines. In drip systems, a progressive reduction in discharge towards the terminal emitters is typically associated with frictional losses and pressure decline along the lateral lines. However, the absence of a substantial decline in discharge towards the terminal emitters suggests that hydraulic losses within the irrigation network were negligible. This can be attributed primarily to the short lateral length (2 m) and the relatively small number of emitters (four per lateral) spaced at 0.5 m intervals, which minimised friction losses and pressure head reductions along the flow path. Consequently, discharge variation between the inlet, intermediate, and terminal emitter positions remained very low. The minor differences observed among emitter positions were likely due to inherent emitter manufacturing variability and experimental measurement uncertainty rather than pressure-induced hydraulic effects. These findings are consistent with the high values of statistical uniformity, emission uniformity, and Christiansen's uniformity coefficient obtained in this study, confirming the ability of the gravity-fed drip irrigation system to maintain a nearly uniform distribution of water along the lateral lines.

The observed uniformity is consistent with the findings of Martinez *et al.* (2024), who reported minimal discharge variation along short lateral lengths operated under low-pressure conditions, resulting in high uniformity indices.

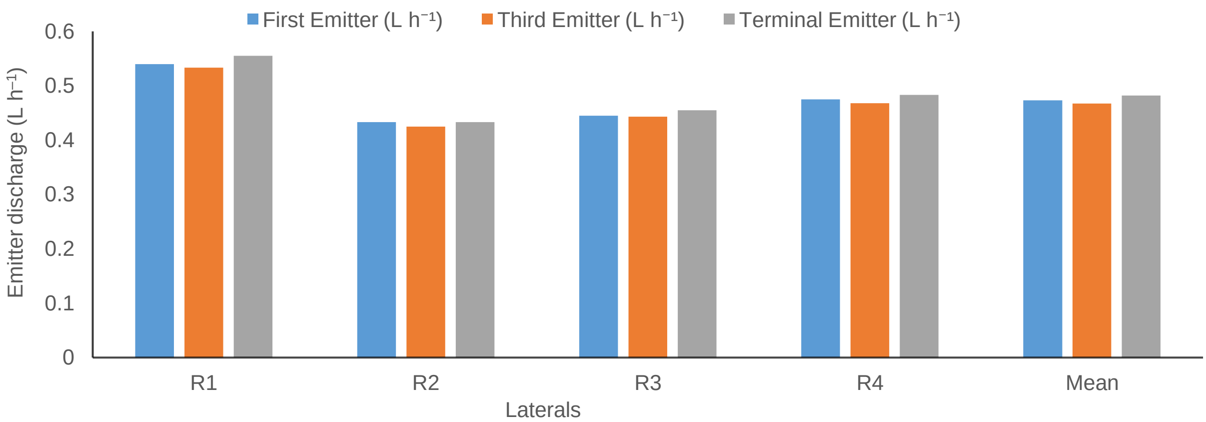

Figure 3: The discharge variation along lateral lines

Table 6: Overall hydraulic performance classification

Parameter	Mean ± SD	Performance Rating
Average emitter discharge (L h^{-1})	0.474 ± 0.049	--------
Coefficient of variation	0.037 ± 0.009	Excellent (Keller and Bliesner, 1990)
Statistical uniformity (%)	96.31 ± 0.91	Excellent (ASAE, 1996)
Emission uniformity (%)	96.14 ± 0.67	Excellent (ASAE, 1996)
Christiansen uniformity coefficient (%)	97.26 ± 0.72	Excellent (ASABE, 1999)

Overall Hydraulic Performance

A summary of the key hydraulic performance indicators of the low-pressure gravity-fed drip irrigation system is presented in Table 6.

The low-pressure gravity-fed drip irrigation system demonstrated excellent hydraulic performance under falling-head operating conditions. The average emitter discharge across the four replicated irrigation units was 0.474 L h^{-1}, indicating consistent emitter operation throughout the irrigation network. The CV averaged 0.037, which is considerably lower than the commonly accepted threshold of 0.10 for excellent emitter performance. This result indicates minimal discharge variability among emitters and suggests that hydraulic conditions within the system remained stable during irrigation. Similarly, the emission uniformity, statistical uniformity, and Christiansen uniformity coefficient averaged 96.14%, 96.31%, and 97.26%, respectively. These values exceed recommended standards for drip irrigation systems and demonstrate highly uniform water application throughout the nursery.

The system was supplied from a 50-L cylindrical storage tank without replenishment during testing; consequently, the available pressure head gradually declined throughout the 60-min. evaluation period. Based on the average emitter discharge and the total number of operating emitters, approximately 7.6 L of water was discharged during each evaluation, representing about 15% of the tank volume. For a cylindrical tank of constant cross-sectional area, this volume reduction corresponds to an approximately proportional decrease in water level and available hydraulic head. Despite this reduction in operating head, the system maintained excellent hydraulic performance. The low coefficient of variation and high uniformity indices indicate that the decline in pressure head had little effect on emitter discharge and overall water distribution.

Furthermore, the small differences among inlet, intermediate, and terminal emitter positions suggest that friction losses along the lateral lines were minimal. The absence of a substantial decline in discharge towards the terminal emitters indicates that pressure losses were adequately controlled within the system layout. The findings indicate that low-pressure gravity-fed systems represent a practical and affordable irrigation technology for smallholder farmers, offering high water application uniformity with minimal energy requirements.

CONCLUSION

This study evaluated the hydraulic performance of a low-pressure gravity-fed drip irrigation system used for irrigating oil palm nursery seedlings under falling-head operating conditions. The results showed that the system maintained stable emitter discharge and achieved excellent hydraulic performance, with low discharge variability and high uniformity indices throughout the irrigation network. The coefficient of variation, emission uniformity, statistical uniformity, and Christiansen uniformity coefficient all exceeded recommended performance standards, indicating highly uniform application of irrigation water despite the gradual reduction in pressure head during operation. The minimal differences in discharge observed among inlet, intermediate, and terminal emitters further demonstrated that friction losses along the lateral lines were limited and did not adversely affect system performance.

In summary, the study demonstrated that low-pressure gravity-fed drip irrigation systems can provide a reliable, energy-efficient, and cost-effective irrigation option for nursery seedling production particularly among smallholder farmers and in areas where access to electricity and conventional pressurised irrigation infrastructure is limited.

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