Archives of Current Research International

Volume 24, Issue 6, Page 299-307, 2024; Article no.ACRI.120375
ISSN: 2454-7077

Assessing Design of Drip Emitters by Evaluating Hydraulic and Manufacturing Performance of Online Drip Emitters

Kunapara A. N. [a*], **Subbaiah R.** [a] **and Patel G. R.** [a]

[a] *Anand Agricultural University, Gujarat, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/acri/2024/v24i6788

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/120375

Original Research Article

Received: 16/03/2024
Accepted: 20/07/2024
Published: 24/07/2024

ABSTRACT

The efficiency of drip irrigation is closely influenced by the accuracy of its design, particularly the hydraulic and manufacturing performance of the emitters. This study investigates the hydraulic performance and flow variation of 8 litres per hour (lph) drip emitters. Discharge rates for 100 emitters were measured at a pressure of 1 kg/cm² to determine the manufacturer's coefficient of variation and the flow variation due to hydraulic factors. The relationship between pressure and discharge was modelled using power function regression, demonstrating a strong correlation between predicted and observed emitter discharge rates, with a root mean square error (RMSE) of 0.56 lph. A design chart was derived from this model, illustrating the relationship between input pressure at the head end and output pressure at the tail end of the system. The manufacturing coefficient of variation for the 100 emitters was found to be 0.0521, classifying the emitters as

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*Corresponding author: Email: akunapara@gmail.com;

Cite as: *A. N., Kunapara, Subbaiah R., and Patel G. R. 2024. "Assessing Design of Drip Emitters by Evaluating Hydraulic and Manufacturing Performance of Online Drip Emitters". Archives of Current Research International 24 (6):299-307. https://doi.org/10.9734/acri/2024/v24i6788.*

"good" according to manufacturing standards. The study provides important understandings for designers aiming to create efficient drip irrigation systems and effective water management strategies. By addressing both hydraulic and manufacturing variations, the study confirms that it is possible to achieve more uniform water distribution, enhance crop yield, and optimize resource utilization.

Keywords: Drip irrigation; hydraulic emitter flow of variation; online emitter; manufacturing coefficient of variation; pressure discharge relationship.

1. INTRODUCTION

Drip irrigation is widely recognized for its excellent distribution uniformity, making it ideal for irrigating vegetables and horticultural crops [1]. It efficiently manages water and fertilizer, saving 27–42% more water compared to other irrigation methods [2-4]. Drip irrigation systems, using emitters and pipes, deliver water directly to plants. Automation efforts, such as a microcontroller-based system, have improved water use efficiency, reducing consumption by 8.6% compared to manual systems and 49.6% compared to check basin irrigation systems [5]. Despite the advantages, practical challenges like poor design, management, and maintenance can reduce efficiency and lead to uneven emitter discharge, sometimes causing over-irrigation and wastage of water and nutrients. Addressing these issues ensures efficient use of water and nutrients and optimizes crop yield.

Planning a drip irrigation system requires careful attention to emitters' hydraulic performance, focusing on pressure drop distribution. Testing the system's hydraulic performance post-installation is crucial for efficiency, as field topography and system design can affect water distribution due to pressure head variations. Research into the relationship between operating pressure and emitter discharge is vital, as increasing pressure variation can lead to higher water loss and reduced system uniformity and efficiency [6]. Properly designed systems can apply water and fertilizer directly to plant root zones, maintaining optimal soil moisture and minimizing loss. Customized systems can also handle challenging terrains [7].

Recent research highlights the importance of optimizing hydraulic performance through various pressures and configurations. Studies by Attia *et al*. (2019) show that the HydroCalc model effectively simulates pressurized systems, noting energy savings with different slopes and lateral lengths. Daccache *et al*. (2010) find that flow regulators stabilize performance amid hydrant pressure fluctuations. Hussain and Gupta (2017) report optimal efficiency at 1.2 kg/cm², while Liu *et al*. (2019) stress the need to maintain pressures above 60 kPa to prevent clogging. Sharu (2022) indicates that lower pressures can still perform well, and Sahu *et al*. (2018) find that pressures between 1.2 and 1.5 kg/cm² maximize efficiency. Bush *et al*. (2016) and Mistry *et al*. (2017) confirm that higher pressures improve uniformity and reduce variability with pressure-compensating emitters.

However, while these studies focus on hydraulic performance and pressure effects, they often ignore the impact of manufacturing variables on emitter efficiency. This study aims to address this gap by evaluating both hydraulic performance across different pressures and the influence of manufacturing factors on emitter functionality, providing a comprehensive analysis that integrates design and operational considerations.

2. MATERIALS AND METHODS

2.1 Experimental Details

To assess the hydraulic performance of 8 lph online emitters, an experiment was conducted in 2022 at the Department of Irrigation and Drainage Engineering, College of Agricultural Engineering and Technology, Anand Agricultural University, Godhra, located at Latitude 22°46'53.8"N and Longitude 73°39'26.2".

The drip irrigation system used for the experimentation comprised several key components. A 2000-liter water tank ensured a sufficient water supply for irrigation needs. At the control head, a 1 hp pump and two types of filters—a hydro cyclone filter and a disc filter—ensured adequate water filtration before distribution. The system's distribution network was thoughtfully designed with durable materials and precise specifications. The main line was made of PVC with a diameter of 75 mm, while the sub-main line was constructed from HDPE and measured 63 mm in diameter. For the lateral lines, LDPE was used, and these lines had a diameter of 16 mm. The lateral lines were spaced 60 cm apart, each extending to a length of 60 meters. The emitters used in the experiment were of the online type with a discharge rate of 8 lph. Emitters were spaced at 60 cm intervals along the lateral lines. This setup allowed for a precise evaluation of different hydraulic parameters and water delivery efficiency specific to the 8 lph emitters as shown in Fig.1.

2.2 Emitter Flow Variations Caused by Hydraulics

Solomon and Keller [8] analyzed the distribution of emission rates in trickle irrigation systems under various conditions. They developed a general expression for determining the pressure at any point within the system's pipe network, assuming a flat field. This expression enabled the calculation of the expected emitter flow rate at any point in the system, based on the emitter flow rate equation. Wu and Giltin [9] demonstrated the following equation for drip irrigation emitter flow:

$$q = kh^{x} \tag{1}$$

In the equation, *q* represents the emitter flow, *k* is the constant of proportionality, *h* is the pressure head, and *x* is the discharge exponent of the emitter. Assuming that all emitters in the system respond to pressure according to this equation, these calculations determine the expected distribution of average emission rates corresponding to the various pressures throughout the system.

The emitter flow variation along a lateral line, caused by hydraulic factors, was determined by emitter flow profiles. Since the emitter profiles are smooth curves in uniform slope situations, the emitter flow variation Wu and Giltin, [10] can also be shown by comparing the maximum and minimum emitter flows and can be expressed as follows:

$$q_{var(H)} = \frac{q_{max(H)} - q_{\min(H)}}{q_{\max(H)}} \tag{2}$$

Where, $q_{var(H)}$ is the emitter flow variation by hydraulics and $q_{max(H)}$ and $q_{min(H)}$ are maximum and minimum emitter flow, respectively. A definite relationship between the UCC and $q_{var(H)}$ was developed by Wu *et al.* [11] and showed that a 10 percent emitter flow variation, $q_{var(H)}$ is equivalent to a Christiansen uniformity coefficient, UCC, 97.5 percent and a 20 percent $q_{var(H)}$ is equivalent to a UCC of 95 percent. The Hydraulic variation of emitter flow usually is expressed statistically by hydraulics coefficient of variation which is

$$V_H = \frac{S_H}{\bar{q}_H} \tag{3}$$

Where, the V_H is hydraulics coefficient of variation of emitter flow, $\bar{q}_H$ is the mean emitter flow and S_H is the standard deviation of emitter flow. In this study, the variations in emitter flow caused by hydraulic factors were investigated. Specifically, emitter flow rates of 2 and 4 liters per hour (lph) were measured under different pressure conditions. The relationship between pressure and discharge was established for all three emitter flow rates.

Fig. 1. Experimental setup of drip irrigation system

2.3 Emitter Flow Variations Caused by Manufacturer

The manufacturing variation of emitter flow usually is expressed statistically by manufacturer's coefficient of variation given by the Wu and Gitlin [10]:

$$V_m = \frac{S_m}{\bar{q}_m} \tag{4}$$

Where, the V_m is manufacturer's coefficient of variation of emitter flow, $\bar{q}_m$ is the mean emitter flow and S_m is the standard deviation of emitter flow. The ASAE interpretation of manufacturing coefficient of variation is shown in Table 1.

Table 1. Recommended classification of manufacture's coefficient of variation

Emitter Type	V_m Range	Classification
Point Source	<0.05	Good
	0.05 to 0.10	Average
	0.10 to 0.15	Marginal
	>0.15	Unaccepted

Source: Design, installation and performance of trickle irrigation system, ASAE, Engineering Practice, 1985, ASAE EP 405

The manufacturing variation of emitter flow exists in any emitter at any section of the lateral line based on a normal distribution. The emitter flow variation caused by the manufacturer and expressed by $q_{\min(m)}$ and $q_{\max(m)}$ can be defined by the Wu and Gitlin [10]:

$$q_{var(m)} = 1 - \frac{q_{\min(m)}}{q_{\max(m)}} \tag{5}$$

Where, $q_{var(m)}$ is the emitter flow variation by manufacturing. The sample included 100 emitters for each discharge rate of 2, 4, and 8 lph. The measurements were conducted under the recommended operating pressure of 1 kg/cm².

2.4 The Total Variation of Emitter Flow

Previous sections show the effect of emitter flow variations caused by hydraulics and manufacturer's variation separately. However, the emitter flow variation for a drip irrigation system in the field was affected by both hydraulics and manufacturer's variation. The total variance can be determined considering that the variation caused by hydraulics and manufacturer can be linearly combined as shown by Bralts *et al.* (1981):

$$V_q^2 = V_H^2 + V_m^2 \tag{6}$$

Where, V_q is the total coefficient of variation caused by hydraulics V_h and manufacturing V_m. The total coefficient of variation can be determined as

$$V_q = \sqrt{V_H^2 + V_m^2} \tag{7}$$

The total emitter flow variation can also be shown by maximum and minimum emitter flow as shown in equation above and proposed by Bralts (1978).

2.5 Root Mean Squared Error (RMSE)

The root mean squared error (RMSE) is a metric that quantifies the agreement between observed and modelled datasets in real units. It is a non-negative metric with no upper limit, and is more sensitive to high magnitude events and peaks. It is computed by taking the square root of the average of the squared differences between observed and modelled values as mentioned below.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{n}|(O)_i - (P)_i|^2}, \ (0 \leq \text{RMSE} \leq +\infty) \tag{8}$$

The RMSE is comparable to other metrics like sum squared error (SSE) and mean squared error (MSE), but it is generally preferred due to its representation in the original units of the data, making it more interpretable. However, RMSE should not be considered in isolation. To assess model performance, it is recommended to use multiple evaluation criteria, such as MAE, R-squared, and visual inspection of the observed versus modelled data. This comprehensive approach ensures a more thorough understanding of the model's accuracy and predictive capabilities.

3. RESULTS AND DISCUSSION

3.1 Hydraulic Performance of Emitter Flow Rate

The hydraulic performance of 8 lph online emitters was thoroughly evaluated by analyzing the relationship between emitter flow rates (q), inlet pressure (h), and other parameters described in the Table 2. The emitter discharge relationship curve for this emitter is depicted in Fig. 2. The experimental data yielded a specific equation for the flow characteristics of 8 lph emitters, represented as:

$$q = 2.46h^{0.48} \tag{9}$$

This equation demonstrates a strong correlation between inlet pressure and emitter flow rate, with a root mean square error (RMSE) of 0.56 lph, indicating high accuracy in predicting flow rates under varying pressure conditions. The observed and predicted value of modelled emitter flow rate is depicted in Fig. 3.

Table 2. Performance characteristics of 8 lph online emitter

Parameter	**Value**
q (lph)	8
k	2.460
x	0.480
$q_{var(m)}$	0.278
q_{var}	0.471
V_m	0.0521
V_m classification	Average
	0.181
RMSE (lph)	0.561
R^2	0.989

Graphical representations of these relationships clearly showed that as inlet pressure increased, the flow rate of the emitters also increased, consistent with the derived equation. The consistent discharge exponent (0.48) across this emitter type suggests uniform hydraulic behaviour in response to pressure changes. These findings underscore the reliability and predictability of 8 lph emitters, crucial for achieving uniform water distribution in drip irrigation systems.

The strong correlation coefficients validate the accuracy of the modelled equations, making them applicable in practical irrigation scenarios to optimize water usage and enhance crop growth efficiency. These results align with previous studies by Deshmukh *et al*. [12], Myres and Bucks [13], and Shashi Kant [14].

Using these equations, the Table 3 demonstrates the flow variations caused by hydraulic factors for 8 lph emitters across different inlet and outlet pressure ranges. This information is essential for designers aiming to understand and manage flow variations in drip irrigation system designs effectively.

3.2 Manufacturing Coefficient of Variation

The assessment of manufacturing variation for the 8 lph online emitters involved evaluating both the manufacturer's coefficient of variation and the emitter flow variation (qvar). A detailed analysis was conducted by measuring the discharge rates of 100 emitters at an inlet pressure of 1 kg/cm².

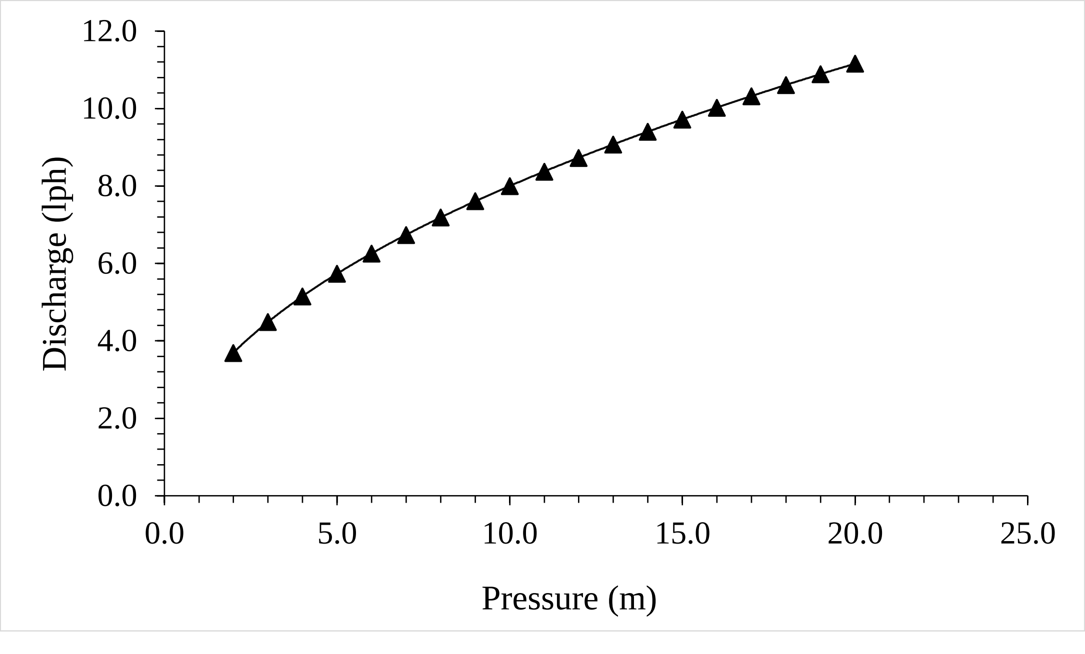

Fig. 2. Pressure discharge relationship curve

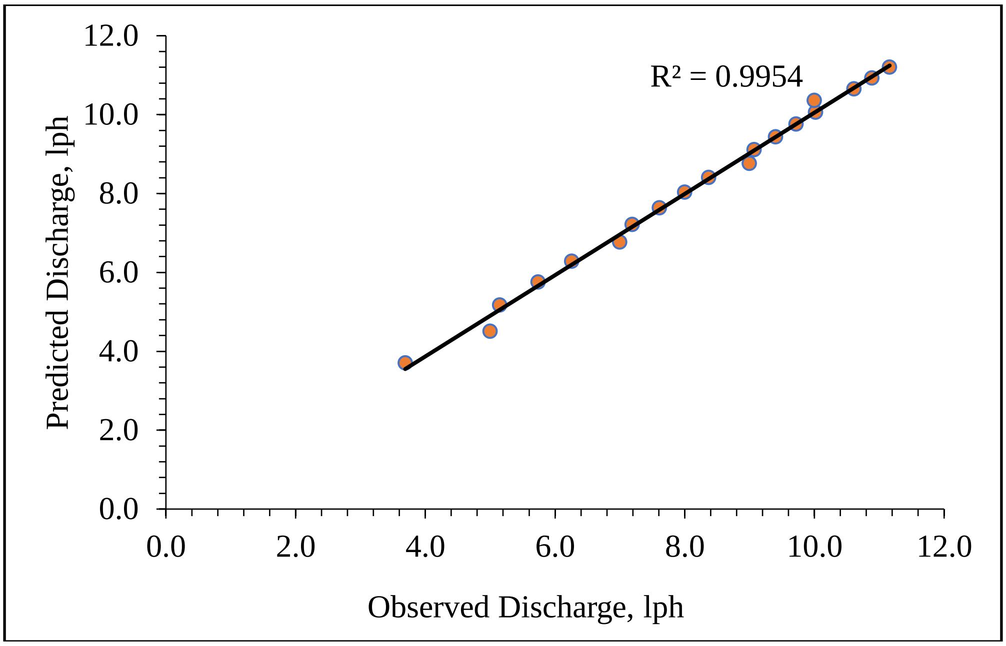

Fig. 3. Observed and predicted emitter flow rate

The manufacturer's coefficient of variation for the 100 emitters of 8 lph emitters was determined to be 0.0521. According to standard manufacturing coefficient classifications, this value categorizes the emitters as "good." This coefficient quantifies the consistency of emitter performance across the batch, indicating minimal variability in flow rates among the tested emitters. Comparatively, experimental tests by Bralts (1978) and Solomon [15] have suggested that manufacturer's coefficients of variation for various emitters or lateral lines typically range from 0.05 to 0.20, further affirming the high quality and uniformity of the 8 lph emitters evaluated in this study.

In addition to manufacturing coefficient of variation, the assessment also included evaluating emitter flow variation, which was found to be 0.278 for the 8 lph emitters. This parameter measures the variation in flow rates attributable to manufacturing processes. Minimizing emitter flow variation is crucial for ensuring consistent water delivery to crops, as even slight deviations can affect irrigation efficiency and crop health.

Understanding and mitigating manufacturing variations are essential for achieving optimal performance in drip irrigation systems. Rigorous quality control measures during emitter production are vital to maintaining uniform flow rates and maximizing the overall efficiency of irrigation operations. By ensuring consistency in emitter performance, farmers and designers can effectively manage water resources and enhance crop yields in agricultural settings [16,17].

3.3 The Total Variation of Emitter Flow

In a real-world drip irrigation system, the variation in emitter flow rate for 8 lph emitters is influenced by both hydraulic and manufacturing variations simultaneously. To quantify the total variation of emitter flow, a lateral line with 100 emitters spaced at 0.6 meters and with a diameter of 16 mm was installed in the field. Each emitter's discharge was recorded under an operating pressure of 1.5 kg/cm². Based on these measurements, the total variation of emitter flow for 8 lph emitters was determined [18]. The total coefficient of variation (V_q) and emitter flow variation (q_{var}) were analyzed as system parameters, which are generally consistent across different soil types but can vary with changes in system parameters such as emitter discharge, lateral spacing, or diameter. In this study, the emitter discharge was varied to assess its impact on these parameters [19].

For the 8 lph emitters, the total coefficient of variation was found to be 0.18, and the emitter flow variation was 0.47. These values indicate significant variability in water delivery among the emitters due to combined hydraulic and manufacturing variations. The higher coefficient of variation and emitter flow variation for the 8 lph

Table 3. Hydraulic variation $q_{var(H)}$ of emitter flow for different inlet and outlet pressure

Outlet Pressure (m)	**Inlet Pressure (m)**																	
	20	**19**	**18**	**17**	**16**	**15**	**14**	**13**	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**
2	0.67	0.66	0.65	0.64	0.63	0.62	0.61	0.59	0.58	0.56	0.54	0.51	0.49	0.45	0.41	0.36	0.28	0.18
3	0.60	0.59	0.58	0.57	0.55	0.54	0.52	0.51	0.49	0.46	0.44	0.41	0.38	0.33	0.28	0.22	0.13	
4	0.54	0.53	0.51	0.50	0.49	0.47	0.45	0.43	0.41	0.38	0.36	0.32	0.28	0.24	0.18	0.10		
5	0.49	0.47	0.46	0.44	0.43	0.41	0.39	0.37	0.34	0.32	0.28	0.25	0.20	0.15	0.08			
6	0.44	0.42	0.41	0.39	0.38	0.36	0.33	0.31	0.28	0.25	0.22	0.18	0.13	0.07				
7	0.40	0.38	0.36	0.35	0.33	0.31	0.28	0.26	0.23	0.20	0.16	0.11	0.06					
8	0.36	0.34	0.32	0.30	0.28	0.26	0.24	0.21	0.18	0.14	0.10	0.05						
9	0.32	0.30	0.28	0.26	0.24	0.22	0.19	0.16	0.13	0.09	0.05							
10	0.28	0.27	0.25	0.22	0.20	0.18	0.15	0.12	0.08	0.04								
11	0.25	0.23	0.21	0.19	0.16	0.14	0.11	0.08	0.04									
12	0.22	0.20	0.18	0.15	0.13	0.10	0.07	0.04										
13	0.19	0.17	0.14	0.12	0.09	0.07	0.03											
14	0.16	0.14	0.11	0.09	0.06	0.03												
15	0.13	0.11	0.08	0.06	0.03													
16	0.10	0.08	0.05	0.03														
17	0.08	0.05	0.03															
18	0.05	0.03																
19	0.02																	

emitters, compared to longer lateral lengths and wider emitter spacings, exacerbate the effects of both hydraulic and manufacturing variations. This exacerbation leads to greater inconsistency in water distribution, potentially affecting crop growth and yield.

Understanding and effectively managing these variations are crucial for optimizing the efficiency and uniformity of water distribution in drip irrigation systems. By doing so, farmers and irrigation system designers can enhance crop yields and maximize the efficient use of water resources in agricultural practices [20,21].

4. CONCLUSIONS

The findings from this study highlight significant implications for the design and implementation of drip irrigation systems, particularly concerning the hydraulic and manufacturing variations affecting emitter flow rates. The observed strong correlation between inlet pressure and emitter flow rate for 8 lph emitters underscores the reliability of predictive models in optimizing water distribution uniformity. By emphasizing the importance of maintaining low manufacturing coefficients of variation (V_m = 0.0521) and minimizing total emitter flow variations (V_q = 0.18, q_{var} = 0.47), this research underscores the critical role of stringent quality control measures in emitter production. These insights are pivotal for irrigation system designers, enabling them to enhance system efficiency, reduce water wastage, and maximize crop yields through precise management of hydraulic parameters and manufacturing standards in drip irrigation technology.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
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