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Development and Evaluation of an Emitter with a Low-Pressure Drip-Irrigation System for Sustainable Eggplant Production

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Abstract: Drip-irrigation can improve uniformity in water distribution, water use efficiency, and crop productivity in the saline and nonsaline regions of South Asia and in Bangladesh where the availability and quality of water resources are scare for sustainable crop production. However, the currently available drip-irrigation systems (DIS) have limitations especially in the design and field performance of emitters. A new type of emitter with low pressure (gravity) was developed, installed and evaluated using the locally produced materials in two locations (nonsaline and saline zones) of Bangladesh. The emitter discharge rate was measured for the variable operating heads of 1.5, 2, and 2.5 meter (m) with 0%, 1%, and 1.5% slopes with eggplant (*Solanum melongena* L.), a commonly grown vegetable in the region. The tested parameters of the emitter were manufacturer coefficient of variation (CV_m), emission uniformity (EU), coefficient of uniformity (CU), and the statistical uniformity (Us) of water application. Our results reveal that the discharge rates of the emitter varied from 3 to 5 L h^{-1} under the operating head of 1.5 to 2.5 m with the slope of 0–1.5%, with better performance of the DIS at 2 m operating pressure head and for slopes of 0% and 1%. The CU of all the test parameters was more than 80%, implying that the DIS was designed and installed with appropriate dimensions for the efficient application and distribution of water to the individual plants, with the emitter performance classified as fair to excellent considering water application and distribution, as well as crop yield. The new emitter used for DIS in field conditions showed that the eggplant yield, water use, and water productivity were greater by 4.6%, 38%, and 70%, respectively, compared to farmers' irrigation practice. We conclude that the DIS has a great prospect to save water, and could be a convenient irrigation water application method for sustainable crop production in saline and nonsaline regions of Bangladesh and similar soil and climatic conditions in South Asia.

Keywords: dripper; hydraulic performance; precision irrigation; uniformity coefficient; water use efficiency

1. Introduction

Traditionally, the most common irrigation method in South Asia and particularly in Bangladesh is the surface flood irrigation. Such methods, which are practiced extensively in the region, lead to excessive uses of irrigation water, and consequently resulting in increased surface runoff, deep percolation and water stagnation, decreased aeration, and reduced water use efficiency. These practices will ultimately lead to reduced yields, increased input costs, and reduced net income. Inadequate and improper maintenance of the irrigation system can decrease the statistical uniformity coefficient (i.e., related to uniformity in water application) to 60% or less, resulting in increased water application to compensate for the decreased application uniformity or reduced yields [1]. Accurate manufacture of the emitter is necessary to achieve improved uniformity. The complexity of irrigation systems and their individual components make it difficult to maintain precision in water application during crop production. These problems need to be addressed to achieve higher water use efficiency and increased crop yields among farming communities.

Reducing water use, saving water, and improving water use efficiency in agriculture are challenging tasks, especially under the current and future climate change conditions. Improved irrigation methods are essential for avoiding water and nutrient leaching from soils as well as reducing groundwater pollution, all of which play an important role in achieving desired crop yields [2]. Drip-irrigation is found to be an effective method for reducing water application and increasing water use efficiency by applying uniform water directly to root zones of each plant, particularly in areas where rainfall is scarce and irrigation water is very expensive [3–5]. Applying a small quantity of water to each plant means that uniform distribution of water is extremely critical. The drip-irrigation system (DIS) is a controlled method of irrigation, consisting of water pump/water tank, filter, pressure gauge regulator, valve, tube (main and sublaterals) and emitters. It maintains the optimum level of water in the crop root zone by slow application of water either directly on land or into the root zone of the crops rather than the entire land surface [6], and improves the water use efficiency through providing precise amounts of water directly to the root zone of individual crops [7]. The heart of the DIS is the emitter, delivering water in small amounts to individual plants rather than broadcasting over the whole field area. It is not necessary to store more water in the soil profile and crop yields are increased by maintaining soil moisture in the root zone close to field capacity.

Although DIS is not new in Bangladesh, its expansion remains limited due to the nonuniformity of water distribution, the small size and height of the water tank required for frequent refilling, and initial high investment cost [8,9]. The uniformity and general performance of DIS is affected by hydraulic design, emitter manufacturer's coefficient of variation, and other factors [10]. The DIS helps reduce the overexploitation of groundwater that partly occurs due to the inefficient use of water under the surface flood irrigation method [11]. Environmental problems associated with surface irrigation like waterlogging and salinity are also completely absent through drip-irrigation [12]. The DIS helps in saving irrigation water, increasing water use efficiency, and increasing crop yields and fertilizer use efficiency [13,14]. In addition to the private benefits, the DIS generates substantial social impacts in the form of enhanced food security and women's participation in agriculture [15,16]. The DIS is adopted extensively in areas of acute water scarcity and especially for crops such as coconut, banana, citrus, tomato, strawberry, and eggplant [17].

Drip-irrigation has currently been practiced in more than 70 countries in 6 million ha [18]. The most common method is surface DIS where lateral and drippers are on the soil's surface. The advantage of surface DIS is ease in installation, inspection, changing, and cleaning emitters that are mainly used for field crops. The system is comprised of simple parts and a machine, which are easily available on the market. Furthermore, the subsequent use of the system's components in multiple years with alternative systems reduces annual production costs. Therefore, many farmers and entrepreneurs are encouraged to cultivate high-value crops (tomato, citrus, strawberry, eggplant, banana) using the DIS, due to its assured and efficient use of water and fertilizers.

Farmers in South Asia, and in particular Bangladesh, use a traditional DIS which results in the nonuniform distribution of water, unknown height of the water tank, and high import prices required from foreign countries. Hence, by considering the economic conditions of smallholders and small field sizes in Bangladesh, the DIS would be expensive especially in terms of initial investments and would hardly be affordable to most small farmers. Furthermore, limited works are carried out in developing and testing the field performance of emitters used with a DIS in Bangladesh, suggesting opportunities to test, modify, or improve the DIS especially in evaluating the emitters' performance. Therefore, the existing low cost DIS, including the emitter, was developed and evaluated under both lab and field conditions. These justifications led us to conduct research work to develop and evaluate the hydraulic performance of a new emitter with the DIS in terms of uniformity of water distribution, which is a function of the hydraulic characteristics of the drip line and emitter. We evaluated a new emitter with a DIS for growing high-value crops such as eggplants in two locations (one saline and another nonsaline) of Bangladesh, which are representative of many other similar locations in South Asia. The specific objectives were to evaluate the hydraulic performance of the emitter with low pressure (gravity) DIS on eggplant yield, and to characterize the effect of head and slope on water distribution uniformity under field conditions in each of those two locations.

2. Materials and Methods

2.1. Development of Emitter with DIS

A new emitter with a DIS was developed to apply water directly to individual plants or a small group of plants through an emitter operating from plastic tubing at low flow rates and low pressures at frequent intervals. Drip tubing and emitters are laid out in, or parallel to, row crops on the soil surface (uses small pipes and tubing). This system may be pressurized with flow emitters or may operate under gravity pressure. The spacing of the emitters, the layout, and cost of the system depend on the crop spacing, roots, and soil characteristics. In this study, a pressure-compensating emitter attempted to provide a constant flow rate to overcome the hydraulic constraints imposed by an orifice, long-flow path emitter. This emitter usually allows only small changes in the emitter flow rate as pressure is changed within a given design range. A compensating emitter may be the only way to achieve uniform water application when slopes are steep or when the topography is hilly and uneven, ensuring that all plants receive, within reasonable limits, the same amount during any irrigation event, indicating the acceptable uniformity of water application. The uniformity of water application from DIS depends on the operation pressure (operating head) and the response of the emitter to that pressure; operating head; distributing the submain and lateral pipe diameter; and length and type of emitter. Generally, individual emitter flow nonuniformity is caused primarily by emitters' manufacturing variations. Therefore, system water application uniformity is the combination of flow variations of all emitters in the system. For the drip-irrigation system's layout, when laterals are very long and placed in a slopy land, it is necessary to maintain the uniformity of flow of emitters. [19].

2.2. System Measurement Parameters for DIS

Based on development principles and availability of materials in the local market, one compensating low discharge type of emitter was developed by the Irrigation and Water Management (IWM) Division, BARI, Gazipur through a local manufacturer in Dhaka, Bangladesh, as shown in Figures 1 and 2, and Table 1. There are two parts of the emitter: (i) upper part and (ii) lower part (Figure 2). The upper part of the emitter was made of high-density polyethylene (HDPE) and the lower part of the emitter was made of polypropylene (PP), which are the cheaper plastic materials available in the market. The granular type of pigment was used for color. The silicon rubber washer (Figure 2c) was used for controlling the water pressure. Based on the properties of the new emitter, the local manufacturer separately made the mold and set to the autoinjection molding machine. After setting the mold, the plastic material was injected into the machine for producing parts of the emitter. Finally, two parts were fitted using the silicon rubber washer. The newly developed emitter was used in the laboratory to evaluate the installation and hydraulic performance during 2017–2018. The test parameters of the DIS, such as manufacturer co-efficient of variation (CV_m), emission uniformity (EU), coefficient of uniformity (CU), statistical uniformity of water application (Us), and head–slope–discharge relationship, were evaluated. A set of laboratory experiments was performed to obtain improved gravity fed DIS. The laboratory DIS consisted of a tank (500 L), disk type filter, one sub main pipe (3/4″ dia), 8 sub-lateral pipes (1/2″ dia.), and 200 emitters (25 emitter/each sub line). A water tank (500 L) was set at 1.5, 2, and 2.5 m height above the emitters manually and maintained water pressure by gauges. The emitter spacing was 0.75 m × 1 m, with emitter-to-emitter at 0.75 m and row-to-row at 1 m as shown in Figure 1.

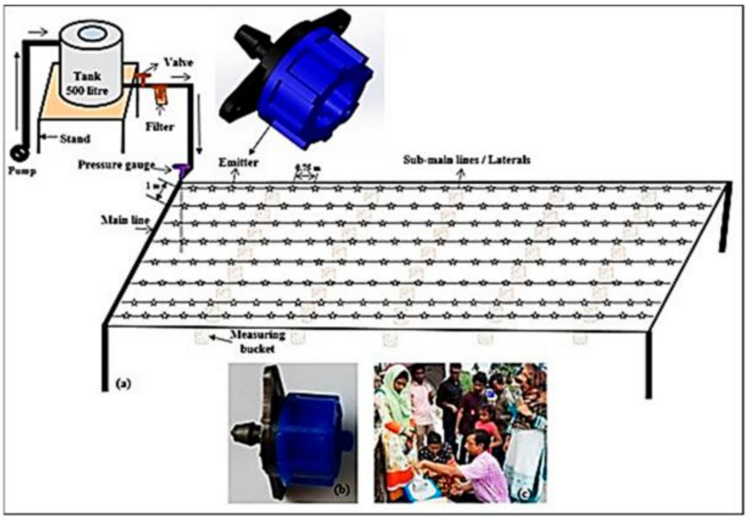

Figure 1. A schematic view of low pressure (gravity) drip-irrigation layout (**a**), new emitter (**b**), and measurement of each emitter discharge for characterization of hydraulic parameters (**a**,**c**).

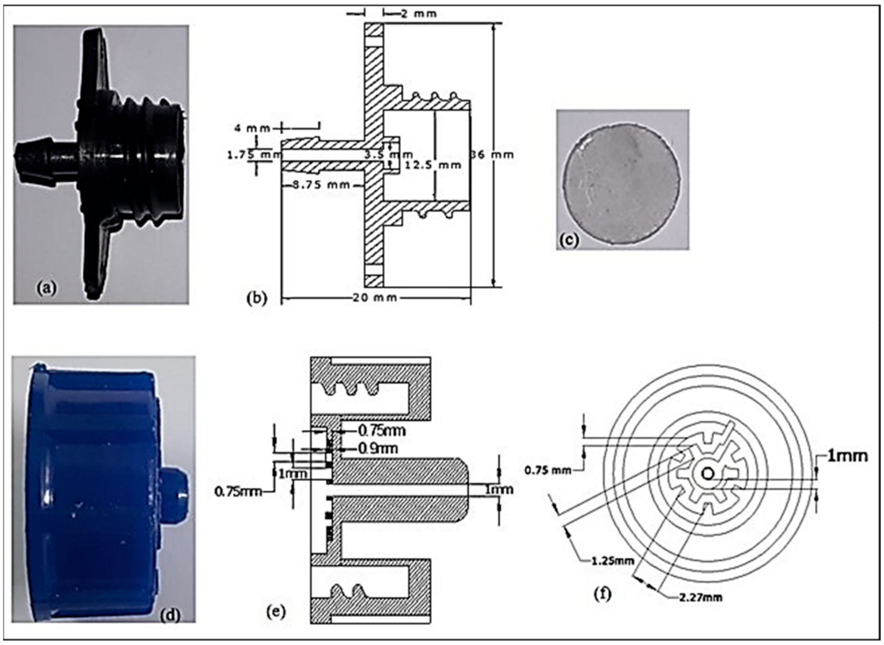

Figure 2. View of emitter properties and cross sectional view with leveling: (**a**) upper part of emitter and (**b**) cross section of the upper part, (**c**) silicon rubber washer, (**d**) lower part of the emitter, (**e**) cross section of the lower part, and (**f**) cross section of the labyrinth.

Table 1. Properties of the new emitter used.

Emitter Parameters		Dimension
Labyrinth Dimensions	Width of flow (mm)	0.75
	Depth of flow (mm)	0.75
	Detention width (mm)	1.0
	Depth of detention (mm)	0.90
	Length of flow (mm)	25
Section of Entry	Dia of entry (mm)	1.75
	Length of entry (mm)	8.75
	Fin spacing (mm)	2.27
	Number of fins	6
	Length of fin (center to center) (mm)	1.25
Coefficient of manufacturer variation (CV_m)		0.04–0.08
Shape of the diaphragm		Circular
Discharge (L/h)		3–5

The submain and lateral lengths used in all test runs were kept 8 m and 20 m, respectively. A $\frac{3}{4}$ inch dia. (19 mm) main pipeline with zero slopes was maintained at each time and eight $\frac{1}{2}$ inch dia. (13 mm) submain pipeline with 3 different slopes of 0%, 1% and 1.5% was used every time under suggested operating 3 different heads (pressure) of 1.5 m (1.5 kPa), 2 m (20 kPa), and 2.5 m (24 kPa). Unused materials from the original 2017 purchase were evaluated in the laboratory using the same pressure regulating valves as those used in the laboratory installment. Five emitters were placed on each lateral line at equal distance, and a total of 40 out of 200 emitters were tested simultaneously for a period of 2 min under different heads (pressures) with 3 different slopes of 0%, 1%, and 1.5%. A disk type filter, controlled valve, and the pressure gauge were used to control the head and pressure for each operation. The water source for tests was deep groundwater with pH, water salinity, and temperature of 7.02, 0.0035 dS m^{-1}, and 28 °C, respectively, using a TRI-METER (model: pH/EC and TEMP-983). Volumetric water pots (measuring 500 mL water beakers) were used for discharge collection, and the collected water was also weighed using a precision digital balance. Water volumes and their weight were collected and recorded manually. The discharge rates of emitters were measured volumetrically (±5%) and the collected water was weighed three times (±2%) for all replications. A stop watch with simultaneously alarming bells (±1 sec) was used to measure flow times correctly. The operating head (pressure) and pressure remained constant during each set of measurements. The operating pressure was measured using pressure gauges at the starting point of the water supply to the system. The test standards procedure [18] was followed to determine the hydraulic parameters of CV_m, EU, UC, and Us.

2.2.1. Manufacturer's Coefficient of Variation (CV_m)

The manufacturer's coefficient of variation (CV_m) is a measure of the variability of discharge of a random sample of a given make, model, and size of the emitter, as produced by the manufacturer and before any field operation. Equation (1) was used to determine the CV_m [20].

$$CV_m = \frac{S_d}{\bar{q}} \tag{1}$$

where, CV_m = manufacturer's coefficient of variation of emitter flow, S_d = standard deviation of emitter flow rates at reference pressure head (l/h), and $\bar{q}$ = mean emitter flow rate in the sample at that reference pressure head (l/h). The classification of CV_m values according to American Society of Agricultural Engineers (ASAE) standards are shown in Table 2.

Table 2. American Society of Agricultural Engineers (ASAE)-recommended classification of manufacturer's coefficient of variation (CV_m).

CV_m	CV_m (%)	Classification
0.05	<5	Excellent
0.05–0.07	5–7	Average
0.07–0.11	7–11	Marginal
0.11–0.15	11–15	Poor
>0.15	>15	Unacceptable

2.2.2. Emission Uniformity (EU)

Emission uniformity (EU) is one of the most frequently used in design criteria for the DIS. It is one of the indices for the evaluation of the DIS. Emission Uniformity (EU) is used primarily to describe the predicted emitter flow variation along a lateral line. To estimate design uniformity in terms of CV_m and pressure variations, the following equation was used [21]. The recommended ranges of design EU by ASAE standards for different conditions are shown in Table 3.

$$EU = 100\left[1.0 - \frac{1.27CV_m}{\sqrt{n}}\right]\frac{q_m}{q_a} \quad (2)$$

where, EU is the design emission uniformity (%), n is the number of the emitter, CV_m is the manufacturer's coefficient of variation of emitter flow, q_m is the minimum emitter discharge rate (l/h), and q_a is the average or design discharge rate (l/h).

Table 3. System classification according to emission uniformity (EU).

EU (%)	Classification	
	Merriam and Keller [22]	Capra and Scicolone [23]
>90	Excellent	High
80–90	Good	Mean
70–80	Acceptable	
66–70	Poor	Low
<66	Unacceptable	

2.2.3. Christiansen's Coefficient of Uniformity (CU_c)

Christiansen's coefficient of uniformity (CU_c) is calculated using Christiansen formula [20].

$$CU_c = 100[1 - \frac{\sum_{i=1}^{n}\left|q_{i-\bar{q}}\right|}{n\bar{q}}] \quad (3)$$

where, CU_c = Christian's uniformity coefficient (%), n = number of emitters used in data analysis, q_i = discharge or volume weight of water collected in the ith emitter, and $\bar{q}$ = arithmetic average discharge/volume of weight caught by all collected emitters (collectors).

2.2.4. Statistical Uniformity of Coefficient (U_s)

Uniformity of water application using statistical terms is defined as:

$$U_s = 100(1 - V_q) = 100\times(1 - \frac{S_d}{q_a}) \quad (4)$$

where, U_s is the statistical uniformity of water application, V_q is the coefficient of variation of emitter flow measurement, S_d is the standard deviation of emitter flow (l/h), and q_a is the average emitter flow measurements. Based on statistical uniformity, system classification is presented in Table 4.

Table 4. System classification according to statistical constant pressure.

U_s (%)	ASAE [24]	Capra and Scicolone [23]
>90	Excellent	High
80–89	Very good	
70–80	Acceptable(fair)	Mean
60–70	Poor	
<60	unacceptable	Low

2.2.5. Flow Variation (q_{var})

The variation of flow (q_{var}) was calculated using Equation (5):

$$q_{var} = \left(\frac{q_{max} - q_{min}}{q_{max}}\right) \times 100 \tag{5}$$

where, q_{var} is the variation of emitter flow (%), q_{max} is the maximum of emitter flow rate (l/h), q_{min} is the minimum of emitter flow rate (l/h).

2.3. Field Validation of the Drip-Irrigation System

The field validation was conducted in the research station in Gazipur (nonsaline zone) and farmers' field of Khulna (coastal saline zone) during the Rabi (dry) seasons of 2017–2018. The soil was silt loam with an average field capacity of 28% and the mean bulk density of 1.45 g/cc. The field experiment was carried out with two treatments replicated thrice in randomized complete block design. The layout of two irrigation methods was the DIS at 3–5 days interval (M1) compared to farmers' practice (M2). Soil was also collected for soil salinity at different growth stages and soil profiles. Soils were sampled from 0–15, 15–30, and 30–45 cm soil depths at the time of sowing to harvest. The electrical conductivity of $EC_{1:5}$ was determined using TRI-METER and converted to actual salinity EC_e of soil water content (dS/m) while using the formula derived from Slavich and Peterson [25]. Standard agronomic crop management practices were followed. The test crop was eggplant cultivar BARI Bt-Begun-2. The spacing was row-to-row 75 cm and plant-to-plant 1 m. The plot size was 210 square meter at Gazipur and 200 square meter at Khulna. The recommended fertilizer rates were N_{175}, P_{60}, K_{132}, S_{23}, Zn_3, and $B_{1.7}$ kg ha^{-1} [26]. All P, S, Zn, B, and organic manure were applied as basal during final land preparation. N and K were applied in four equal splits as a side dressing in eggplant rows at 20, 40, 60, and 80 days after planting. The seedlings were planted on 23 November 2017 at Gazipur and 6 December 2017 at Khulna, and crops were harvested on 9 April 2018 at Gazipur and 30 April 2018 at Khulna. Data on pan evaporation and precipitation (rainfall) were collected from the Khulna and Gazipur weather stations to estimate irrigation water requirement (IW, mm) for full irrigation using the following equation [27].

$$IW = E_p \times K_p \times A \tag{6}$$

where, IW is the amount of irrigation water amount (liter), A is the area of the plot (m^2), E_p is the cumulative pan evaporation (mm), and K_p is the pan coefficient and was considered 0.7 [27].

Total seasonal crop water use (SCWU) was calculated as the sum of total irrigation water applied (IW), effective rainfall (P_e), and soil water contribution (SWC) between plantation and final harvest, expressed by the following equation [28]:

$$SCWU = IW + Pe \pm SWC \tag{7}$$

The yield contributing characters and fruit yield of eggplant were recorded from the plants during the experimental period. Three plants were randomly chosen to measure the yield components from each treatment. Economical yields (t/ha) were measured from the plants harvested from the selected rows of each plot. Yield was manually harvested. Water productivity (WP) was calculated as the ratio of yield and total seasonal water use, which was expressed by the following equation [28]:

$$WP\left(kg/m^3\right) = \frac{CY \times 100}{SWCU} \quad (8)$$

where, WP is the water productivity (kg/m^3), CY is the crop yield (t/ha), and SCWU is the amount of seasonal crop water use (mm).

3. Results and Discussion

3.1. Relationships between Operating Pressures and Emitter Discharge Rates

The discharge rates for each pressure at various slopes were taken for eight lateral lengths (20 m each). The mean discharge rate of the emitter for each operating pressure with various slopes indicated that as the slope of the low pressure (gravity) DIS increased, the discharge rate of the emitter also slightly increased (Figure 3). The emitter discharge rates had almost similar trends at 1.5 and 2 m operating pressures, with 0% and 1% slopes, respectively. The average discharge rate was found around 3.8 1/h for 1.5 m operating pressure head, 4.5 1/h for 2 m operating pressure, and 4.8 l/h for 2.5 m operating pressure with slopes of 0%, 1%, and 1.5 %, respectively. The hydraulic performance of DIS indicated that with increased operating pressure, the flow rate of the emitter increased but there was only a slight effect of slopes on the emitter's discharge. With the increase of pressure heads from 1.5 to 2.5 and increase of slopes from 0% to 1%, the discharge rate also increased, but it slightly decreased at the 1.5% slope (Figure 3).

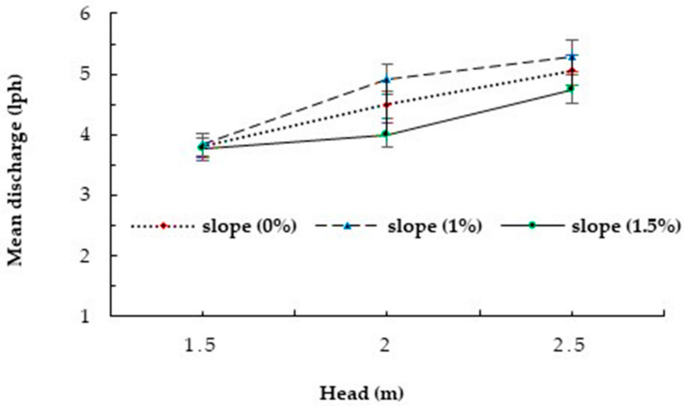

Figure 3. Emitter mean discharge rates for each operating pressure (head) with various slopes. Bars indicate the error percentage (5%).

For the 2.5 m operating pressure, the discharge rate slightly increased as the water pressure at the inlet was raised. The relationship of discharge rate and pressure head indicated that the increase in pressure head increased the discharge. The relationship between the discharge and pressure head plays a key role in the emitter selection [29]. In this study, the DIS with the new emitter resulted in a nearly similar trend of discharge, though it varied with the change of supply water pressure. It is observed that the emitter discharge variation also could occur due to pressure differences [30].

3.2. Relationships between Emitter Discharge Rates along the Lateral (Submain) Line

The relationships between the emitter discharge rates with their corresponding position in the lateral line indicated that for 2 to 2.5 m pressure heads with 0% and 1% slope, there was no increasing or decreasing tendency in the discharge rates (Figure 4). The discharge rate was found almost similar for each lateral line, while for the 1.5 m pressure head with a 0% to 1.5% slope, the variation of discharge rate increased. However, emitter discharge rate variation was higher for a lower operating pressure head than for a higher one, and the discharge variation was higher for a higher slope than a lower one [31]. In general, however, there were no trends in responses in terms of increasing or decreasing the discharge rate of emitter with respect to operating pressure and slope.

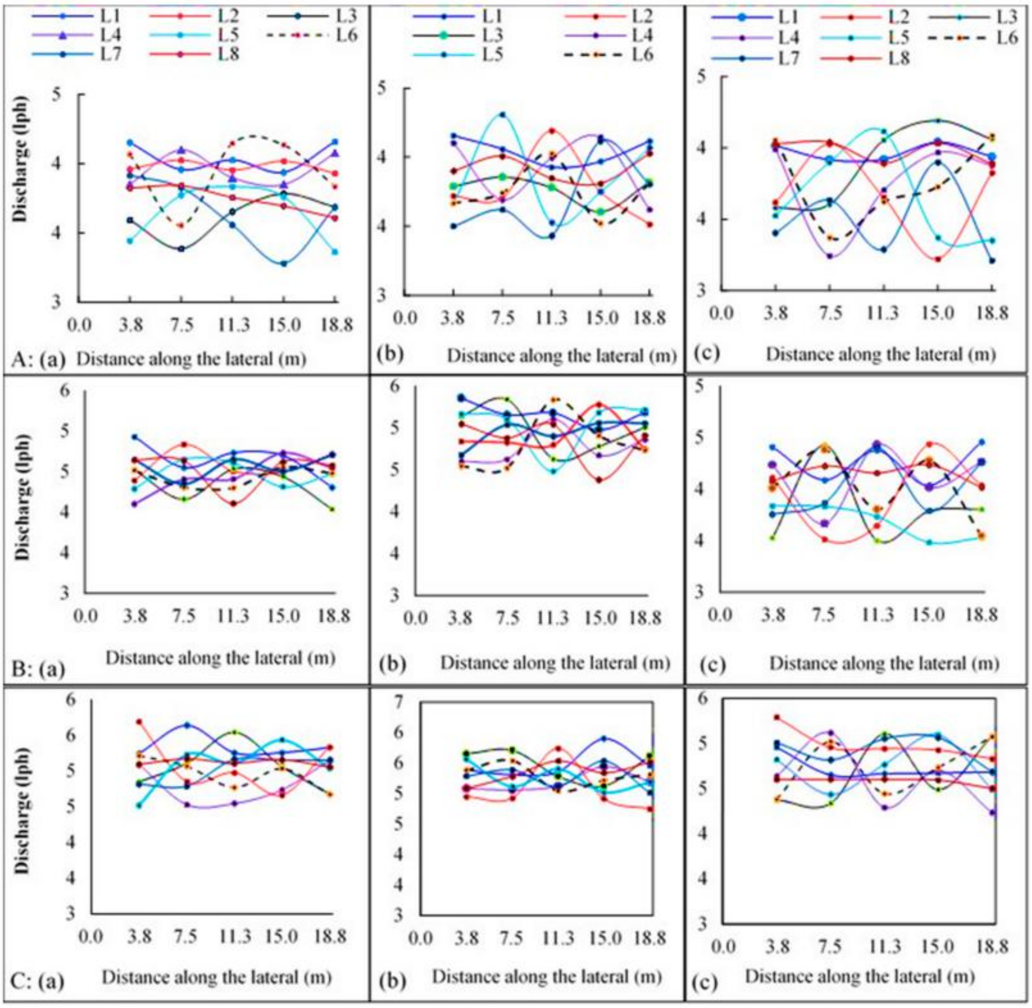

Figure 4. Emitter discharge rates along the lateral length at different operating pressures with various slopes, (**A**) 1.5 m operating pressures with (**a**) 0%, (**b**) 1%, and (**c**) 1.5% slope; (**B**) 2.0 m operating pressures with (**a**) 0%, (**b**) 1%, and (**c**) 1.5% slope; and (**C**) 2.5 m operating pressures with (**a**) 0%, (**b**) 1%, and (**c**) 1.5% slope.

3.3. Observed Test Parameters

3.3.1. Relationship of the Manufacturer's Coefficient of Variation (CV_m)

The coefficient of variation (CV_m) for each operating pressure for various slopes showed variations in emitter CV_m for varying pressures and slopes (Table 5). The results (Table 5) indicate that CV_m for 2 m pressure head with 0% and 1% slope performed average, while with 1.5% slope it performed as marginal (Table 2), as recommended by the ASAE [20]. Similarly, CV_m for the 2.5 m pressure head with 0% and 1.5% slope was 0.06 indicating average performance, but with 1% slope it was less than 0.05. The variation of CV_m depends on the manufacturer's variation, caused by pressure and heat instability during emitter production. In addition, a high CV_m could occur due to a heterogeneous mixture of the local materials used in the production of the emitter [26]. The typical value for CV_m ranges from 2% to 15%, although higher values are possible [32,33]. The hydraulic performance of DIS showed that the discharge flow rate of the emitter increased with increase in pressure, and the coefficient of variation increased with decrease in pressure, indicating that the pressure head affects the discharge rate of the emitter, which was also reported by [34]. The manufacturing and flow variation coefficients were considered excellent in all evaluations when the operating time did not influence the emitters' hydraulic performance. The emitter's discharge rate increased with the increase in pressure, and the coefficient of variation increased with the decrease in pressure. Similar results were reported by Pranav et al. [34].

Table 5. Test parameters of hydraulic performances.

Head (m)	Slope (%)	CV_m *	EU (%)	CU_c (%)	U_s (%)	q_{var} (%)
	0	0.060	84.79	95.28	94.02	21.1
1.5	1	0.057	88.01	95.22	94.25	20.3
	1.5	0.057	85.18	93.37	92.35	21.9
	0	0.045	88.10	94.82	95.53	18.1
2.0	1	0.055	87.78	95.41	94.46	19.5
	1.5	0.078	85.68	93.33	92.70	21.9
	0	0.057	88.55	95.66	94.34	20.5
2.5	1	0.040	89.18	96.60	95.15	19.5
	1.5	0.057	88.22	95.21	93.31	20.0

* Here, manufacturer's coefficient of variation (CV_m), emission uniformity (EU), statistical uniformity (U_s), and flow variation (q_{var}).

3.3.2. Emission Uniformity (EU)

The design emission uniformity (EU) tested for each pressure for different slopes showed EU above 80% for all operating pressures (Table 6). It can be interpreted that the emitter had good emission uniformity values and performed better especially under very low pressure for various slopes. The system classification is supported by ASAE standards as shown in Table 3 [21]. The coefficient of determination (R^2) was higher for 2 m head (Table 6), indicating that the system was efficient in obtaining better yield.

Table 6. Linear relationships of hydraulic test parameters for different operating pressures and slopes.

Parameters	*Slope (%)	Linear Regression Model *	R^2	**Head (m)	Linear Regression Model **	R^2
	0	y = 1.88x + 83.38	0.838	1.5	y = −1.075x + 87.86	0.376
EU	1	y = 0.585x + 87.15	0.607	2	y = −1.21x + 89.60	0.847
	1.5	y = 1.52x + 83.32	0.869	2.5	y = 0.585x + 86.92	0.351
	0	y = 0.19x + 94.87	0.204	1.5	y = −0.955x + 96.53	0.773
CU	1	y = 0.69x + 94.36	0.851	2	y = −1.595x + 98.27	0.970
	1.5	y = 0.92x + 92.13	0.733	2.5	y = −0.225x + 96.27	0.101
	0	y = 0.16x + 94.31	0.040	1.5	y = −0.835x + 95.21	0.648
Us	1	y = 0.45x + 93.72	0.913	2	y = −1.415x + 97.06	0.981
	1.5	y = 0.98x + 91.16	0.878	2.5	y = −0.515x + 95.29	0.312

* y = coefficient of uniformity (%), * x = submain (lateral) slope (%); ** y = coefficient of uniformity (%), and ** x = head (m).

3.3.3. Christiansen's Coefficient of Uniformity (CU_c)

Christiansen's coefficient of uniformity (CU_c) for each pressure for different slopes showed CU_c of above 90%, indicating excellent water application and was quite significant for the evaluation of the uniform distribution of water for the plant (Table 6) [20]. The uniformity coefficient of determination (R^2) was higher for 2 m head with 1% slope (Table 6), indicating that the DIS is excellent and could be better for high value crop cultivation.

3.3.4. Statistical Uniformity (U_s)

The statistical uniformity (U_s) for each pressure at various slopes showed more than 90 percent for each operating pressure head with various slopes (Table 6). The statistical uniformity coefficient of determination (R^2) was also greater at 2 m head with 1% slope. Hence the emitter can be considered as excellent [23,24] and indicating the acceptable limits for water application.

3.3.5. Flow Variation (q_{var})

The emitter flow variation (q_{var}), calculated by considering the minimum and maximum discharge rates in the submain lines for each pressure, showed lower flow variation indicating a better quality emitter. The results indicate that the emitter had flow variation values within the range of 21.1%; 20.3%, 21.9%, and 20.5%; 19.5%; 20% with respect to 0%, 1%, and 1.5 % slope, respectively, at 1.5 and 2.5 m pressure heads, while the flow variation values were 18.1, 19.5, and 21.9 for 2 m pressure head. According to [30], if the flow variation value of a drip system is less than 10%, its performance is considered as excellent; if it is within 10–20% range then the drip system can be considered as good. The results indicate that for 2 m pressure head with 0% and 1% slope, its flow variation values were as good, except for the 1.5% slope which was considered as acceptable. For the 2.5 m pressure head, the emitter had no situation where flow variation can be considered as good at all pressure situations.

3.4. Yield, Water Use, Water Productivity, and Soil Salinity

Yield, water use, and water productivity of eggplant under drip and traditional irrigation methods are shown in Table 7. Total marketable eggplant yield in DIS (M1) was greater by 4.6% compared to the traditional method. The results indicate that when less amount of irrigation water was applied, drip-irrigation method, there was almost 38% reduction in irrigation water and increased yield compared to M2. The results revealed that DIS could be an option for irrigation water supply based on water utilization and yield compared to the traditional irrigation method for the saline and nonsaline areas of Bangladesh and other regions or countries with similar climatic conditions. The DIS saved on average around 38% SCWU. Likewise, the WP was improved by 70% compared to traditional irrigation over two the locations, Khulna and Gazipur (Figure 5). The DIS with reduced amount of irrigation water could improve the physiological response, which can maintain more yield compared to the traditional method. Changes in soil salinity varied from 2.2 dS/m (November 2017) to 9.6 dS/m (March 2018) in 45 cm soil profile with 15 cm increments (Figure 6). The greater changes in soil salinity occurred during the growing season, February/March 2018, with traditional irrigation practices. Similar trends were observed for the other soil profiles. This study further shows that the salt accumulation was around 23% lower (on average) in drip-irrigation than in traditional farmers' practices in 0–45 cm soil depth. Figure 6 also indicates that the soil's salinity was not substantially greater in DIS than in the traditional irrigation system due to continuous soil wetting in the root zone of the plant. Drip-irrigation thus could be practiced with brackish water (low salinity) for eggplant cultivation in salt-affected areas. The DIS is adopted extensively in areas of acute water scarcity and especially for field-grown crops such as coconut, banana, citrus, tomato, cotton, strawberry, and eggplant [17], to achieve sustainable irrigation management practices and crop yield. In addition, the drip-irrigation method helps save irrigation water, increase water productivity, and increase crop yield [13]. Evidence shows that water use efficiency increases by up to 100% if the DIS is properly designed and managed [14]. Our results indicate that the overall quality of the emitter was better for nominal discharge, and the tested hydraulic parameters of emitter in the current study could be used for the design, operation, and selection of the manually operated irrigation systems which could be used for small farms.

Table 7. Yield and yield components of eggplant under drip-irrigation and compared with farmers' irrigation practices at Khulna and Gazipur during 2017–2018.

Location	Treatment	Fruit/Plant (no.)	Fruit Weight/Plant (kg)	Fruit Yield (t/ha)	Crop Water Use (mm)	WP (Kg/m^3)
Khulna	M1	56a	3.12a	41.62a	197	22.25a
	M2	47.33c	2.94b	39.21b	306	12.81b
Gazipur	M1	24.33a	2.24a	29.91a	187	15.99a
	M2	25.66a	2.16a	28.88a	302	9.57b

M1: drip-irrigation at 3–5 days interval, M2: farmers' practice/traditional furrow irrigation (M2).

Figure 5. Field-view of eggplant cultivation under the drip-irrigation system at Khulna and Gazipur locations during 2017–2018.

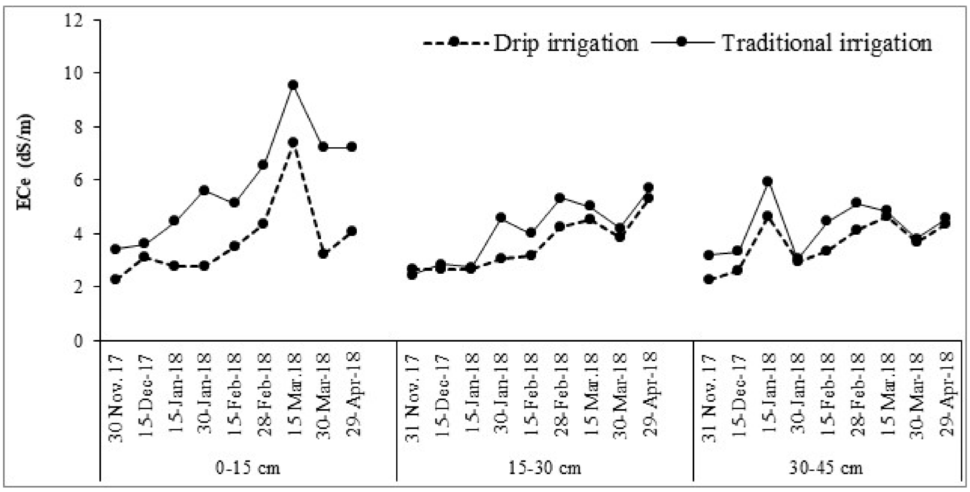

Figure 6. Variations of soil salinity dynamics expressed as EC_e of soil solution ($EC_{1:5}$) over the soil profile during the crop growth season of 2017–18, at the saline area.

4. Conclusions

High irrigation water distribution uniformity is essential for the drip-irrigation system to reduce water losses in fields. In this study, the performance of the new emitter with the low-pressure (gravity) drip-irrigation system was found better for a 2 m operating head with a 0% and 1% slope. The uniformity of water application was more than 80%, indicating that the emitter was designed on the basis of proper dimensions and locally available materials. Field validation of the drip-irrigation system increases yield, water use, and substantially improves water productivity by 4.6%, 38%, and 70%, respectively, compared to farmers' irrigation practices. Low-pressure (gravity) drip-irrigation systems could be widely used in saline and nonsaline areas where irrigation water is scarce and expensive.

Further studies are required to confirm our findings concerning uniform water application and for improving water use efficiency for sustainable irrigation and crop production practices.

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Abbreviations

CU	coefficient of uniformity
CV_m	manufacturer coefficient of variation
CY	crop yield
DIS	drip-irrigation system
Dia	diameter
DU	distribution uniformity
EU	emission uniformity
IWM	irrigation and water management
IW	irrigation water
Pe	effective rainfall
SCWU	seasonal crop water use
SWC	soil water contribution
Us	statistical uniformity
WP	water productivity

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