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A Prediction Model of Labyrinth Emitter Service Duration (ESD) under Low-Quality (Sand-Laden Water) Irrigation

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Abstract: The reasonable evaluation of emitter service duration and appropriate emitter selection have become an important way to improve the efficiency of drip irrigation systems, and also provide a basis for the wide application of drip irrigation technology in agricultural and landscape irrigation. During field irrigation, both irrigation uniformity (CU) and relative average flow (Dra) play crucial roles in crop growth, so it is not appropriate to evaluate emitters based on one of these factors alone. In this study, a new comprehensive index for measuring the operating life of emitters—the emitter service duration (ESD) was established for selecting emitter products in the field. The indoor drip irrigation experiment was carried out under nine kinds of sand-laden water, and the emitters' service duration, based on irrigation uniformity and emitter flow, was tested. By analyzing the individual effects and the comprehensive effects of them, the comprehensive measurement index of the ESD was established and the Pearson bivariate correlation analysis was used to explore the influencing factors. The results showed that the lower the quality of the irrigation water, the smaller the value of the ESD, which meant that the emitters were more likely to be blocked. Different irrigation water sources had different effects on the ESD, which were mainly caused by the characteristic size. Two dimensionless characteristic parameters (W/D and $A^{1/2}/L$) are significantly correlated with ESD. Based on W/D and $A^{1/2}/L$, the ESD prediction model was obtained and the accuracy could reach 86%. It could provide an accurate method for selecting emitters under different water source conditions, which is beneficial for the safe, efficient, and long-term operation of a drip irrigation systems using a low-quality water source.

Keywords: low-quality water irrigation; drip irrigation; emitter clogging; evaluation

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1. Introduction

Drip irrigation can significantly improve water use efficiency, grain yield, and quality [1–4], which play a major role in solving the constraints of agricultural water shortage. However, the emitter is the key factor restricting the further promotion of drip irrigation technology. The use of low-quality water sources (saline, sand-laden water, or treated sewage) for irrigation can increase the clogging, reduce irrigation quality, increase maintenance costs and shorten the service duration of drip irrigation systems [5–8] and could also lead to uneven soil water distribution and low yield or low-quality crops [5,6]. Solid particles are the main component of clogging substances [7–9]. The suspended sediment in agricultural irrigation water source poses a challenge to drip irrigation technology [10,11]. Therefore, for sand-laden water resources, it is crucial to predict the irrigation service duration of the emitters and carry out an effective comparison and selection of emitter products.

The emitter service duration is an important index for measuring the merits and demerits of emitter products in field application and it is also the factor that most farmers concerns. Since the direct expression of emitter clogging is flow reduction, according to the Chinese Micro-irrigation Standard Specification (SL/T 67.2-1994) and the treatment method of emitter clogging (ISO/TC 23/SC 18/WG5 N4), the irrigation times were selected as the irrigation life of the emitters corresponding to the last irrigation when the relative average flow was lower than 75% (based on the relative average flow) [5,12,13] and the anti-clogging ability was studied. However, the uniformity of drip irrigation should also be taken into account in the field application of emitters [14,15]. According to the Agricultural irrigation standard (GB/T 17187-2009), the irrigation uniformity of drip irrigation tape should be higher than 80%. When the irrigation uniformity is lower than 80%, the number of irrigation times corresponding to the last irrigation is set as the irrigation life (based on the irrigation uniformity) [16–18]. During field irrigation, both irrigation uniformity (CU) and relative average flow (Dra) play crucial roles in crop growth; it is not appropriate to evaluate emitters solely based on one of them. A new comprehensive index is needed for measuring the operating life of emitters.

In addition, the anti-clogging ability of emitters in practical application has also been analyzed and studied, and many evaluation methods and prediction models have been produced. The results show that different studies have different suggestions for the optimal structure size of the emitters for prolonging service duration and reducing the risk of blockage. Thus, in addition to emitter flow [19], channel length and width [7,20], and average cross-section speed, there are other factors that determine service duration, it is also affected by water quality characteristics [21–24]. Therefore, the anti-clogging ability of the emitters cannot be evaluated only by rated size. Mohammad [25] introduced a method based on thorough analysis of different calibration datasets to study the pollutant-mixing mechanism in open channels that generates large uncertainty in the estimation of longitudinal and lateral dispersion coefficients (Kx and Ky). Then, they [26] also developed ML models based on various setting parameters and optimization strategies coming from evolutionary and classification contents which provided reliable and physically consistent predictions of scouring propagation rates regarding their comparison with scouring tests. Zhang [27] proposed and established a method based on the random trajectory model in the Lagrangian coordinate system. It took the particle pass rate as the evaluation index. Zhou [28] proposed an evaluation method for the anti-clogging ability of emitters in regenerative water drip irrigation systems based on the characteristic parameters of flow channels, but there were significant differences in the evaluation for different water sources and different types of emitters. At present, there is no prediction model for emitter service duration in low-quality sand-laden water that characterizes the two indexes comprehensively: uniformity and relative average flow.

To consider the emitter service duration, the paper sets ESD as a comprehensive index to achieve: (1) based on the relative average flow and irrigation uniformity, the ESD is proposed to evaluate the operating life of an irrigation system comprehensively; (2) according to the different irrigation water sources, a prediction model of irrigation performance is established, and the applicability and effectiveness in different low-quality water sources are verified; (3) based on the ESD, the structural characteristic parameters of emitters are used as the reference for selecting appropriate emitters for low-quality water sources.

2. Materials and Method

2.1. Materials and Devices

Three non-pressure compensation emitters were selected (Table 1). Rated pressure and rated flow rate were set by the manufacturer (Yangling Runwo Water Saving Co., Ltd., Xianyang, China), and flow coefficient, flow index, and pressure-flow relationship curve (Table 2) were determined by a hydraulic performance test (GB/T 17187-2009). Yangling tap water was selected as the test water (Table 3).

Table 1. Types and fundamental dimensions of emitters.

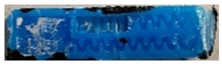
Types	Rated Pressure (kpa)	Rated Discharge (L/h)	Length Width Depth (mm)	Internal Flow Channel Structure
E1	100	3	$224 \times 0.63 \times 1$	
E2	100	1.5	$100 \times 0.68 \times 0.33$	
E3	100	3.5	$170 \times 1.2 \times 0.5$	

Table 2. Hydraulic performance and basic parameters of emitters.

Types	Emitter Manufacture Deviation (%)	Pressure–Flow Relation Equation (L/h-kpa)	Correlation Index (R^2)	Flow Index/x	Flow Coefficients/k
E1	4.07	$y = 0.2909x^{0.5245}$	0.9872	0.5245	0.2909
E2	4.63	$y = 0.1687x^{0.4842}$	0.9826	0.4842	0.1687
E3	3.21	$y = 0.2433x^{0.5995}$	0.9922	0.5995	0.2433

Table 3. Water quality parameters of Yangling tap water.

Parameters	Values	Parameters	Values	Parameters	Values	Parameters	Values	Parameters	Values
pH	7.89	NH_4^+ (mg/L)	0.218	CO_3^{2-} (mg/L)	60.817	K^+ (mg/L)	1.09	Cl^- (mg/L)	11
Conductivity (uS/cm)	243	Mg^{2+} (mg/L)	2.89	PO_4^{3-} (mg/L)	0.02	Na^+ (mg/L)	5.70	Ca^{2+} (mg/L)	28.80

Due to the large amount of sediment required for the experiment, industrial quartz sand was used as a substitute for sediment particles. As silicate minerals, quartz sand is hard, wear-resistant, stable, and the SiO_2 content is 98.2%. Density is 2.66 g/cm^3, and bulk density is 1.65 g/cm^3. The physical properties of them are the same. In addition, the pure composition of quartz sand (more than 98% silica) is more conducive to the analysis of the clogging process under an individual effect, reducing the interference of test errors caused by the introduction of other substances.

Three particle size segments of 0–0.054 mm, 0.054–0.075 mm, and 0.075–0.1 mm were selected. The sand was divided into three grades according to different mass percentages. Based on the irrigation water quality standard, the concentration of suspended matter in irrigation water (mass concentration $\leq$ 0.1 g/L) was more than 10 times, and the sediment concentration in muddy water was set as 1.8 g/L (L), 2.8 g/L (M), and 3.8 g/L (H) to test the clogging degree.

The irrigation test system is shown in Figure 1. The test device consisted of a water storage tank with a stirring function, a water pump, pressure sensors, pipes, laterals, and emitters. The water tank was a cylindrical bucket with a height of 1.55 m and a diameter of 0.83 m at the bottom. The sand was mixed evenly through the guide vane connected with the mixer. The rated head of the self-priming pump was 20 m, the accuracy of the pressure sensor was 0.01 kpa, and the range was 0–0.6 Mpa. The laterals were about 8 meters long, and the same emitter to be tested was installed every six laterals.

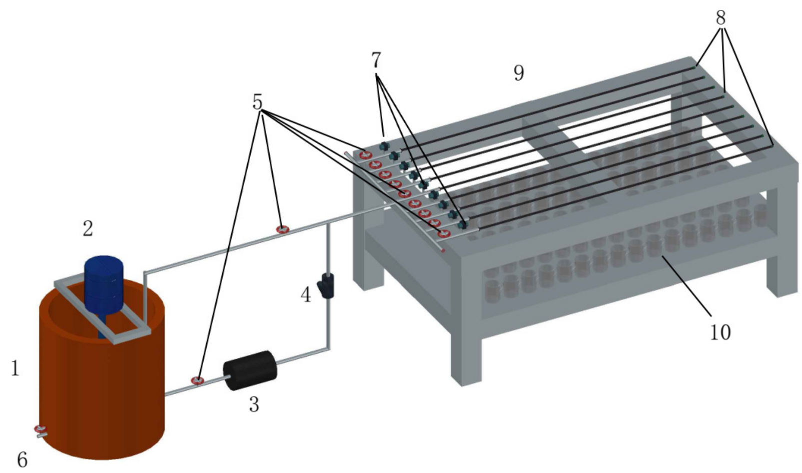


Figure 1. Test system layout. Note: (1). Water supply tank; (2) mixer; (3) water pump; (4) filter; (5) water inlet valve; (6) water source drain valve; (7) pressure sensor; (8) water outlet valve; (9) emitters; (10) measuring cup. Description: 1. The filter (4) is used to avoid accidental larger particles entering the system, which would affect the test results. 2. After the sand is added, the water supply system is thoroughly stirred to ensure the uniform distribution of quartz sand particles in the water. 3. After each treatment, the tested emitters were removed. 4. During flushing, the inlet valves (5) were opened to clean the lateral, then the inlet valves were closed and the drain valve was opened (6) to clean the water supply tank (1).

2.2. Experimental Design

The experiment used the intermittent muddy drip irrigation. The irrigation event occurred twice a day for 2 h each time, and each treatment was repeated twice. The irrigation cycle of each test (excluding the repeated test) was 20 days. Water temperature was measured by an industrial-grade temperature thermometer (range −30 °C to 100 °C, accuracy 0.1 °C) before irrigation. If an irrigation cycle ended, the irrigation also was stopped. After each treatment, the pipes were cleaned and the drip irrigation tapes were replaced.

An orthogonal experimental design was used to organize the grain size and grading, and then it was completely combined with the sediment concentration, to explore the blockage-sensitive particle size of the emitters under the sand-laden water irrigation. Sediment concentration, particle size, and grading were taken as factors in the orthogonal experiment design, and the factors were represented by A, B, and C, respectively. Three levels were considered for each factor. The factors and levels are shown in Table 4. A total of 9 treatments were generated.

Table 4. Factors and Levels.

Factors and Levels	Sediment Grain Size (mm)		Sediment Concentration (g/L)		Grading (%)	
Numbers	**Levels**	**Codes**	**Levels**	**Codes**	**Levels**	**Codes**
1	0–0.054 mm	a	1.8	L	35b-65a	A
2	0.054–0.075 mm	b	2.8	M	35c-65a	B
3	0.075–0.1 mm	c	3.8	H	35c-65b	C

Note: grading represents the mass ratio of the terms to the total sediment weight. For example, level A, 35b-65c represents the sediment configuration consisting 0% c, 35% b, and 65% a.

2.3. Evaluation Index and Determination Method

(1) Flow and relative average flow

The flow rate was measured by the weighing method. When the irrigation event was carried out for 1 h 50 min, the plastic measuring cup was placed under each emitter for 10 min after ensuring that the working pressure of the test system was stable at this stage.

To reduce the error caused by pressure fluctuation in the test process, the percentage of the average flow to the rated flow was defined as the average relative flow (Dra) of the emitter. The flow measured in the test was corrected by the temperature difference formula (Yinguang Jiang et al., 2014).

$$\mathrm{Dra} = \frac{\sum_{i=1}^{n} q_i}{n} / q_c \tag{1}$$

where, Dra is the relative average flow of the emitter, %; q_c is the rated flow calculated according to the pressure-flow relationship curve, L/h; q_i is the flow of each drip irrigation tape, L/h.

(2) Christiansen uniformity

$$\mathrm{Cu} = 1 - \frac{\overline{\Delta q}}{\overline{q}} \tag{2}$$

$$\overline{\Delta q} = \frac{\sum_{i=1}^{n} |q_i - \overline{q}|}{n} \tag{3}$$

$$\overline{q} = \frac{\sum_{i=1}^{n} q_i}{n} \tag{4}$$

where, $\overline{\Delta q}$ is the average deviation of flow, L/h; $\overline{q}$ is the average flow rate, L/h; q_i is the flow rate, L/h. In actual field irrigation, the irrigation uniformity coefficient Cu should not be less than 0.8.

(3) Gradating and particle size composition of clogging substance

After irrigation, all emitters were taken from the drip irrigation tape, collected and numbered. Malvern particle size analyzer was used to analyze the gradating of the clogging substance, and to determine the particle size and gradating composition.

2.4. Index of ESD

The concept of emitter service duration (ESD) was proposed to evaluate the irrigation life of emitters comprehensively. ESD can cover the irrigation life based on average relative flow and the irrigation life based on irrigation uniformity. It adopts the weighted value of the two irrigation life indexes to reflect the service time, and comprehensively measures the irrigation life based on average relative flow and irrigation uniformity:

$$\mathrm{ESD} = \alpha L_q + \beta L_{cu} + b \tag{5}$$

where, L_q is the irrigation life based on average relative flow, that is, the service duration of the system when the average relative flow is lower than 75%, h;

L_{cu} is the irrigation life based on irrigation uniformity, that is, the service duration of the system when the uniformity of irrigation is lower than 80%, h;

ESD is the weighted value of the irrigation life based on average relative flow and the irrigation life based on irrigation uniformity and represents the service duration of the emitter in field application.

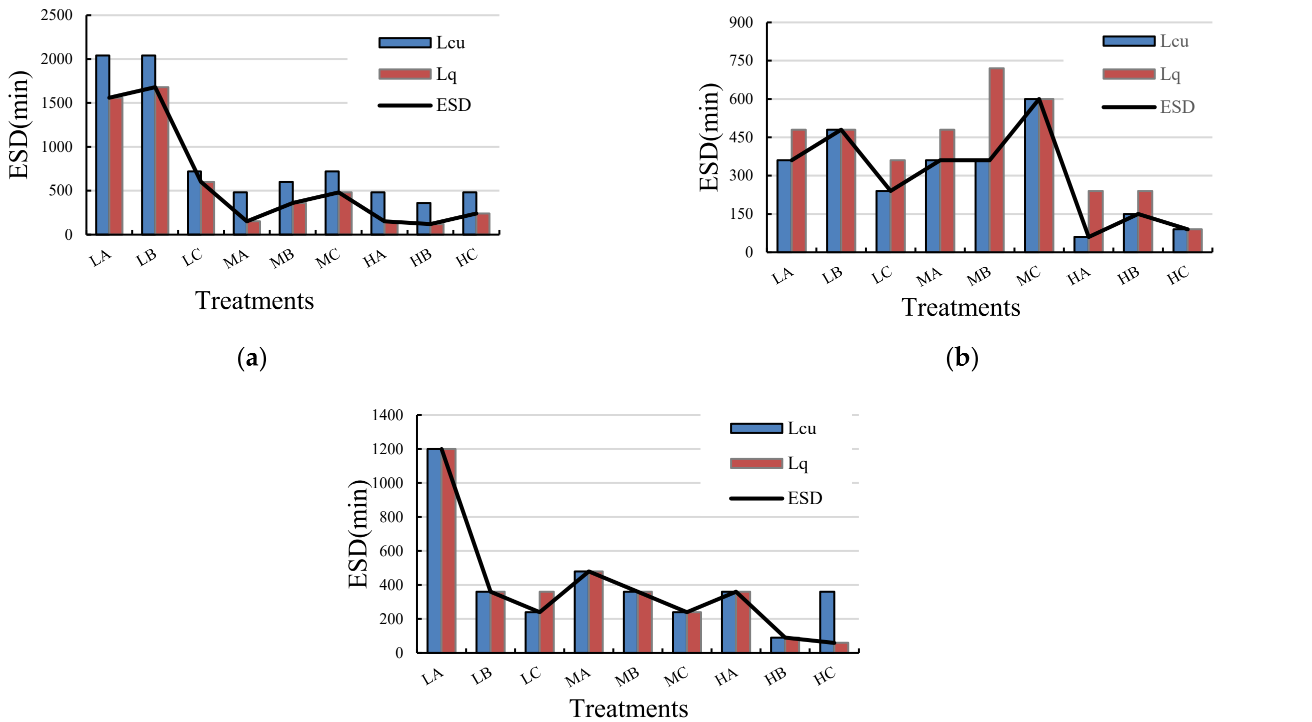
2.5. Data Analysis

Bivariate Pearson correlation was used to analyze ESD and the structural characteristics of the emitter including initial outflow (Q), flow path length (L), flow path width (W), flow path depth (D), cross-sectional area (A, equal to W × D), average cross-sectional velocity (v, equal to Q/A), the two dimensionless ratios between the width and depth of the emitter channel (W/D) and the cross-sectional area and length ($A^{1/2}$/L) (Li et al., 2018), as well as the correlation between the sediment concentration, particle size and grading to determine the main influencing factors; Then, linear regression analysis was used to quantify the correlation between the comprehensive index and influencing factors. SPSS (version 22.0, IBM Analytics; www.ibm.com/legal/copytrade.shtml. Accessed on 03 December 2021) software was used for statistical analysis. p (=0.05) was used to determine the significance of independent variables.

3. Results

3.1. Evaluation Based on EDS

Figure 2 shows the changes in the irrigation duration based on average relative flow and irrigation uniformity, and ESD under sand water irrigation. The service duration of the three kinds of emitters decreased with the increase of sediment concentration and particle size, but the decreasing degree was different. Among them, except E1, which had a larger flow channel size, the irrigation duration based on irrigation uniformity of the other two emitters was less than that based on average relative flow. It is proved that it is too optimistic to consider only the irrigation duration based on average relative flow as the criterion to determine the service duration of the emitter. In practical application, especially in the case of low-quality water source irrigation, before the overall flow drops to the blockage identification standard, local blockage often leads to the failure to complete the task of uniform irrigation.



(**a**) (**b**) (**c**)

Figure 2. EDS under different treatments. (**a**) E1, (**b**) E2, (**c**) E3.

The development trends and irrigation duration based on average relative flow and irrigation uniformity of E1 were not different (Figure 2a). In the range of low concentration and small particle size, the anti-clogging ability of E1 was prominent, but with the increase in them, the service duration decreased quickly. The irrigation duration based on average relative flow and irrigation uniformity of E2 increased in the range of small sediment concentration. However, in the range of small sediment size, the performance was poor, which may be due to the flocculation. In some working conditions, the irrigation duration based on average relative flow and irrigation uniformity of E2 was suddenly separated, which may be related to the occasional blockage of the single emitter. E3 had a good consistency in irrigation life based on both, and the overall trend was not much different from E1. However, because the overall size was much smaller than E1, the service duration values were smaller. With the increase of sediment in the irrigation water source, the service duration was not a steady decline, but a decline in volatility. This is similar to a blockage in the irrigation process, and the longest service duration conditions of E1 and E2 were not optimal conditions, which may be related to the sensitivity of the emitters to the particle size and sediment concentration.

3.2. Direct Estimation of ESD

The concept of emitter service duration (ESD) was developed to evaluate, fully and accurately, the service duration of emitter products in the field. The essence is the smaller value between irrigation duration based on average relative flow and irrigation uniformity, both of which have a direct relationship to the service duration. Therefore, ESD can be directly estimated by them. Linear regression was used to analyze the correlation between them, and the three indexes showed a significant linear regression relationship. Therefore, the direct estimation equation of ESD can be obtained (When the irrigation duration based on average relative flow and irrigation uniformity are both 0, the ESD should also be 0, so the regression equation should pass through the origin):

$$\mathrm{ESD} = 0.606\mathrm{L_q} + 0.303\mathrm{L_{cu}} \left(\mathrm{R}^2 = 0.9881\right) \tag{6}$$

3.3. Influencing Factors of ESD

According to the analysis of the ESD, E1 was more stable and had a longer service duration compared with the other emitters due to the large flow channel. E3 was more stable but had a shorter service duration. The reasons for the fluctuation of E2 under different treatments and the sensitive factors of the emitters need further analysis. SPSS 22.0 software was used to analyze the irrigation life index, and the relationship between it and the flow channel structure parameters, the sediment characteristics of the irrigation source, was analyzed by the bivariate correlation analysis and paired sample T-test.

3.3.1. Structural Characteristics of Emitters

Bivariate correlation analysis was conducted on the characteristic parameters and ESD, such as emitter characteristic size (L, W, D, $A^{1/2}/L$, and W/D), rated flow rate (Q), and average flow rate of section (v) to determine the characteristic parameters that significantly affected the emitter clogging under the condition of drip irrigation with sand-containing water. The results are shown in Table 5. It can be seen that most structural characteristic parameters are correlated or significantly correlated with irrigation duration based on average relative flow and irrigation uniformity, respectively, which are considered to have an impact on the ESD. The dimensionless factors W/D and $A^{1/2}/L$, which are correlated with both of them, were selected as the reference variables of ESD and the basic variables of the emitter selection due to the significant regression relationship and comparison convenience.

In addition, the estimated values of L and Min (W, D) are positive, indicating that the larger the value, the longer the ESD and the stronger the anti-clogging ability. This is consistent with the research results of some scholars (Wei et al., 2006; Zhou et al., 2019; Li et al., 2006). Min (W, D)/L, W/D, and $A^{1/2}/L$ represent the weight of the section size and the length of the channel. A larger cross-section area and shorter channel length mean ideal ESD. It can be seen that it is not comprehensive and reasonable to use a single parameter to represent the ESD, because a single factor cannot determine the shape or service duration of the emitters. In addition, Q and v in the table did not reach a significant level, indicating that they did not have a significant impact on the blockage in this experiment, which may be caused by the small numbers of types of emitter, but it cannot be considered that they had no impact on the blockage.

Table 5. Correlation analysis with characteristic parameters and irrigation life as bivariate ($p < 0.05$).

Irrigation Life	Based on Average Relative Flow				Based on Irrigation Uniformity			
Parameters	Pearson Coefficient	p	T	Significance	Pearson Coefficient	p	T	Significance
Rated flow (Q)	0.154	0.444	−3.044	No correlation	0.231	0.247	5.551	No correlation
Flow channel length (L)	0.496	0.009	16.662	Significant correlation	0.474	0.012	4.026	Significant correlation
Average section velocity (v)	−0.198	0.322	5.825	No correlation	−0.503	0.007	5.512	Extremely significant correlation
Min (W, D)	0.495	0.009	−5.737	Significant correlation	0.474	0.013	5.573	Significant correlation
Min (W, D)/L	−0.419	0.030	−6.243	Correlation	−0.425	0.027	5.577	Significant correlation
W/D	−0.604	0.001	−3.750	Extremely significant correlation	−0.487	0.010	5.555	Significant correlation
Cross section area A = W × D	0.332	0.090	−5.739	No correlation	0.365	0.010	5.573	Significant correlation
$A^{1/2}/L$	−0.601	0.001	6.241	Extremely significant correlation	−0.519	0.006	5.577	Extremely significant correlation

3.3.2. Sediment Concentration and Gradation

The use of low-quality water sources for irrigation is crucial to the rational planning of agricultural water resources. To solve a series of problems caused by low-quality water source irrigation and to avoid frequent replacement of irrigation equipment due to the short service life, it is necessary to choose irrigation equipment suitable for different working conditions. It is an important step to evaluate the relationship between the service duration and the irrigation water source for the rapid and accurate selection of the appropriate emitter products for different low-quality water sources and sediment conditions.

As shown in Figure 3, when sediment particle size and gradation were the same, ESD decreased as sediment concentration increased, which was consistent with the blockage rule of emitters, but the degree of decrease was different, which is related to the sensitivity of emitters to sediment concentration. ESD of E1 under MA and HA, E2 under LA and MA, E3 under MB, LB, MC and LC were the same. The low sensitivity of the corresponding emitters at this concentration means the grading occupation has a greater influence on ESD than the sediment concentration at this treatment. There was no significant difference between E3 and E1 under LA treatment. Under MC treatment, the applicability of E2 was more prominent. The emitter selection needs to be discussed according to the sediment concentration and particle size in the irrigation water source. Therefore, the particle size of sand blocked in the channel of emitter products was analyzed, and the results are shown in Figures 4–6.

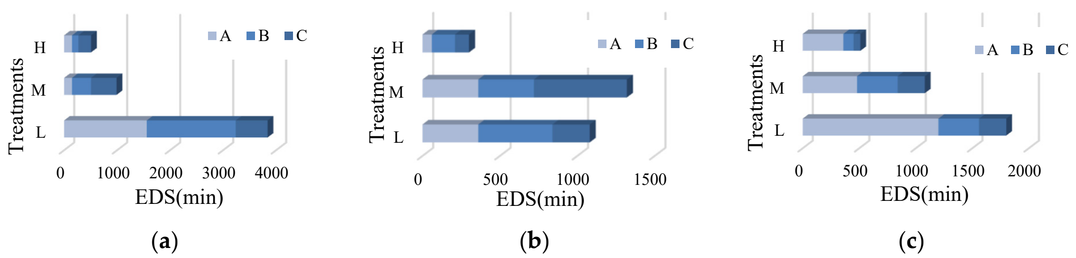


Figure 3. ESD of each emitter with different concentrations. (**a**) E1, (**b**) E2, (**c**) E3.

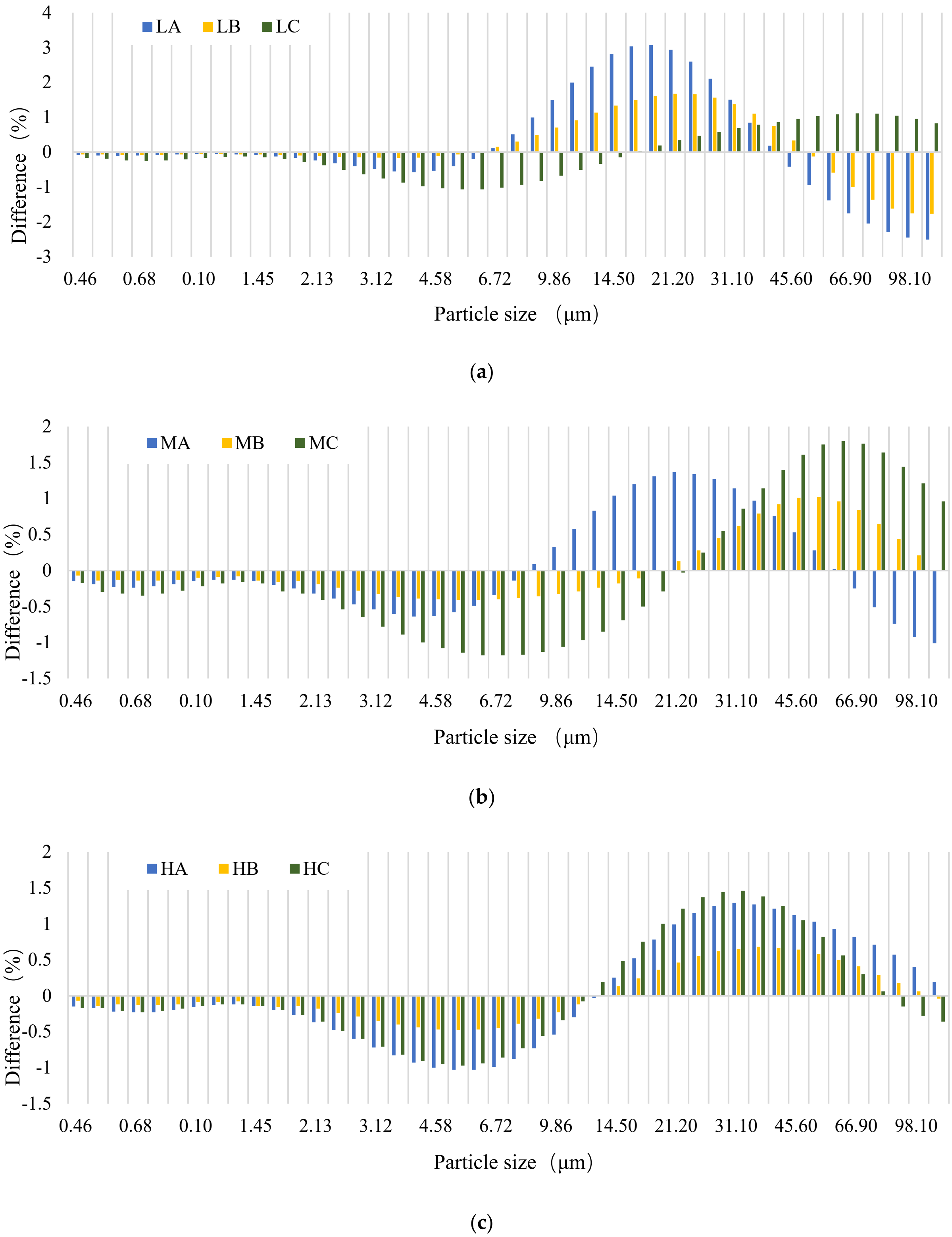
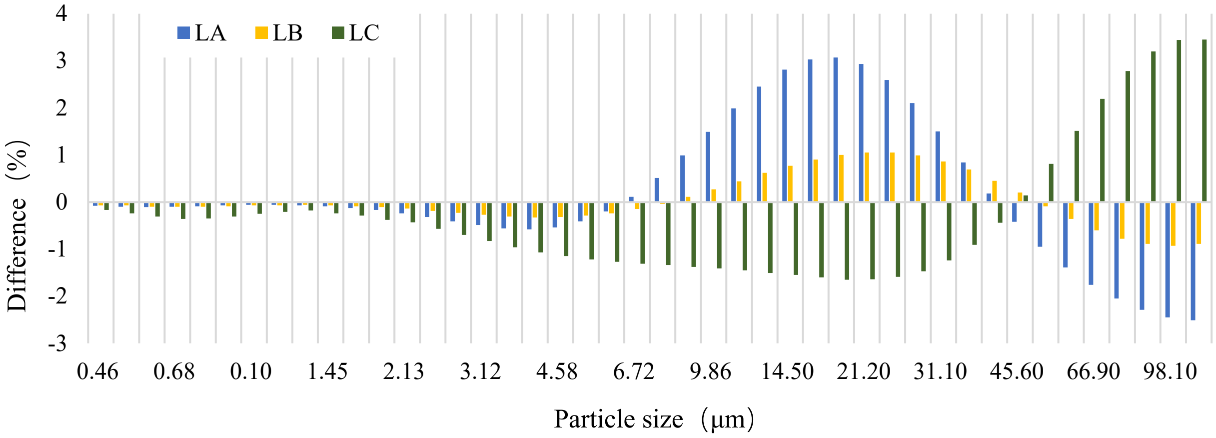
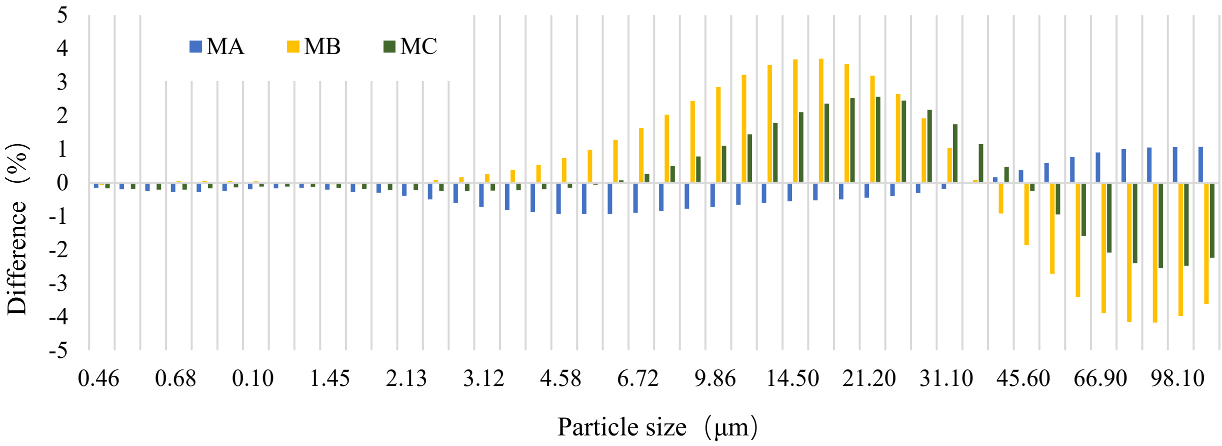


Figure 4. Particle size distribution of clogging sediment in E1 with different sand concentrations. (**a**) Low sand concentration, (**b**) medium sand concentration, (**c**) high sand concentration.



(**a**)



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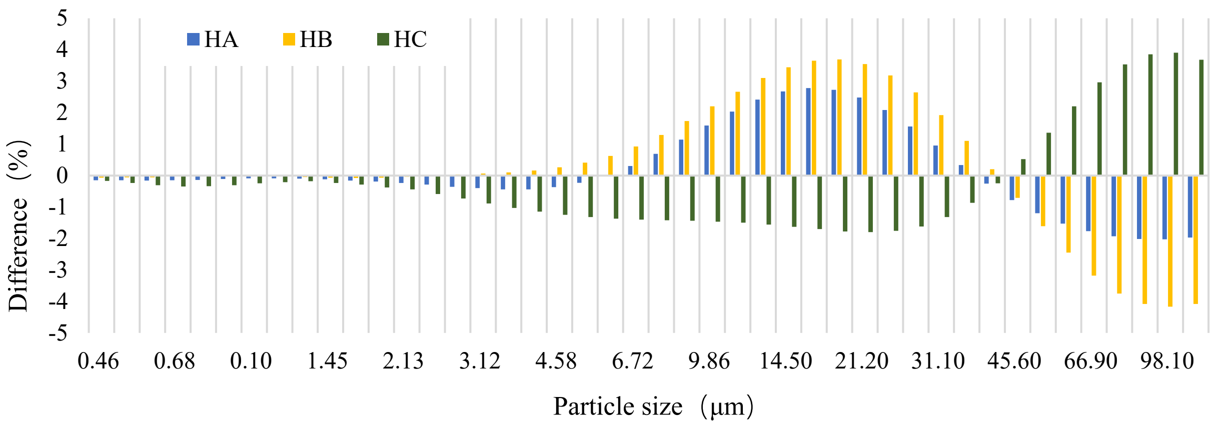

(**c**)

Figure 5. Particle size distribution of clogging sediment in E2 with different sand concentrations. (**a**) Low sand concentration, (**b**) medium sand concentration, (**c**) high sand concentration.

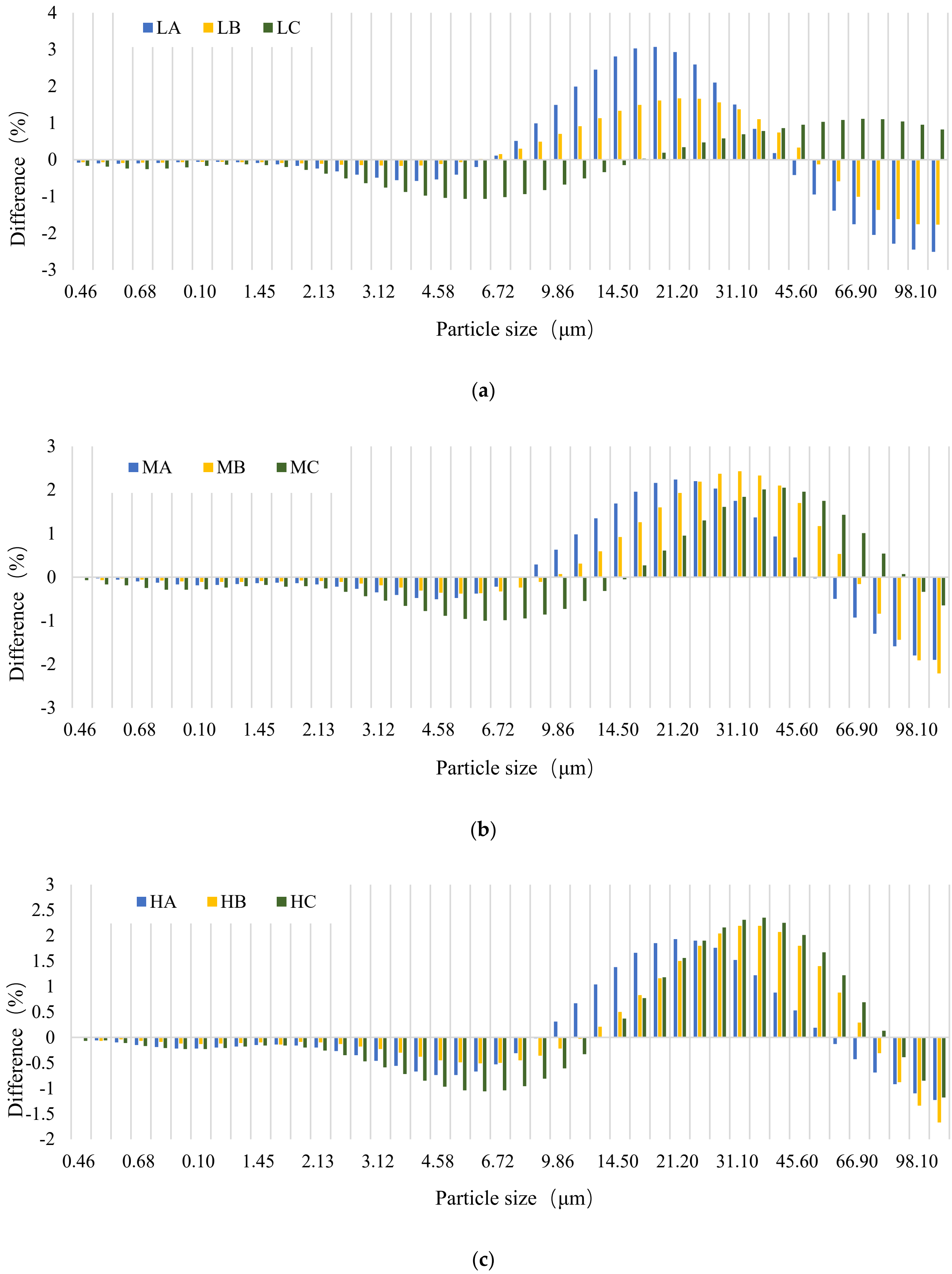

Figure 6. Particle size distribution of clogging sediment in E3 with different sand concentrations. (**a**) Low sand concentration, (**b**) medium sand concentration, (**c**) high sand concentration. Note: The ordinates in Figures 4–6 show the difference between the sediment gradation from the outlet of the emitters and that from the irrigation source, where the lower part (below × axis) is the sediment that is blocked in the flow channel.

Different emitters have different particle size sensitivities with different concentrations. When E1 is used for irrigation, the sand that causes blockage is generally in the small particle size range from 0 to 0.054 mm. There were very few clogs due to large sizes in the 0.075–0.1 mm range. This is because small sediment particles tend to settle by gravity, collide and bond to form a flocculation structure under water turbulence action, which causes the emitter blockage. However, the clogging caused by 0.075–0.1 mm particle size sediment occurs in the condition of high concentration. Because the sedimentation rate t with large particle size increases due to the high sand concentration, it makes it easy to close up and leads to clogging. According to the decline of the average relative flow of E1 during the system operation, the sediment concentration directly determined sediment particle collision probability. The clogging of E1 was a process of sediment particle size redistribution and gradual accumulation, so the clogging process was relatively slow.

Due to the small flow channel size, E2 and E3 were not able to transport large particles. Before the small particle had formed flocculation and blocking structures, the interior channel had been clogged by the large particles. So the particle size that caused the blockage of E2 and E3 was concentrated in the range of 0.054–0.1 mm. Compared with E1, E2 and E3 had a faster and sudden clogging process. The relative average flow rate of most emitters drops to 0 suddenly, and there is no gradual decrease similar to that of E1, which is also due to the direct clogging effect of larger particles. The sediment particle size is the main factor affecting the emitter blockage. The most usual clogging particle size is 3–5% of the ratio of the channel width and channel depth (W/D). It is also between 16 times and 25 times the $A^{1/2}/L$. Based on this, it is necessary to compare and select the emitter products or treat the irrigation water source according to the emitter size and the particle size which easily caused the blockages.

4. Discussion

4.1. ESD Estimation Based on Characteristic Parameters and Irrigation Water Source

Correlation analysis was used to explore the relationship between the ESD and the characteristic parameters of the emitters. The dimensionless factors W/D and $A^{1/2}/L$, which are related to the ESD, were selected as the reference and basis variables. The combined action of the structural parameters resulted in differences in internal water flow and pressure and changed the blockage possibility. The key point of this paper is to judge the emitters performance during the operation with a drip irrigation system by taking the structure size of the emitters as the reference standard and choosing reasonable emitters for irrigation.

Therefore, under different water source irrigation (different sediment concentrations and particle sizes), the characteristic parameters W/D and $A^{1/2}/L$ were correlated with ESD. Significant regression analysis was conducted on the three factors. The model accuracy and the influence proportion of W/D and $A^{1/2}/L$ on the dependent variables were comprehensively considered. The revised ESD prediction model was shown as follows:

$$ESD = 1.837 \times (A^{1/2}/L)^{3/2} - 5.582 \times W/D \ (R^2 = 0.53) \tag{7}$$

where, ESD is the emitter service duration, h. A is the cross-sectional area of the channel, mm^2. L is the total length of the flow channel, m. W and D are, respectively, the width and depth of the flow channel, mm.

Since there is no correlation between W/D and $A^{1/2}/L$, the ESD is determined by $A^{1/2}/L$ and W/D. However, the fit goodness (R^2) was low and could not be effectively predicted according to different irrigation conditions. Therefore, according to the treatment corresponding to the irrigation condition, linear regression was carried out to obtain the relationship equation between the ESD and the characteristic parameters under each irrigation treatment (Table 6).

Table 6. ESD and characteristic parameter equation under treatments.

Treatments	ESD and Characteristic Parameter Equation
LA	$L_A = 4.236 \times (A^{1/2}/L)^{3/2} - 12.505 \times W/D$ ($R^2 = 0.77$)
LB	$L_A = 6.057 \times (A^{1/2}/L)^{3/2} - 23.775 \times W/D$ ($R^2 = 0.94$)
LC	$L_A = 2.035 \times (A^{1/2}/L)^{3/2} - 7.230 \times W/D$ ($R^2 = 0.94$)
MA	$L_A = 0.051 \times (A^{1/2}/L)^{3/2} + 2.96 \times W/D$ ($R^2 = 0.99$)
MB	$L_A = 1.025 \times (A^{1/2}/L)^{3/2} - 1.864 \times W/D$ ($R^2 = 0.99$)
MC	$L_A = 1.812 \times (A^{1/2}/L)^{3/2} - 5.104 \times W/D$ ($R^2 = 0.97$)
HA	$L_A = 0.046 \times (A^{1/2}/L)^{3/2} + 1.520 \times W/D$ ($R^2 = 0.72$)
HB	$L_A = 0.407 \times (A^{1/2}/L)^{3/2} - 0.943 \times W/D$ ($R^2 = 0.99$)
HC	$L_A = 0.866 \times (A^{1/2}/L)^{3/2} - 3.294 \times W/D$ ($R^2 = 0.96$)

4.2. Feasibility and Accuracy of the ESD Model

To verify the feasibility and accuracy of the predicted model, the available data were collected from the studies on emitter clogging. The accuracy of the established estimation model could be further verified before it was applied. Due to different irrigation conditions and research purposes (most studies did not report all the structural parameters of the emitters used), it is difficult to find suitable emitters for verification. We summarized 21 types of emitters, and the results show that the accuracy of the ESD prediction model reaches 86%, which means that it is feasible and accurate to apply the model to predict the emitter service duration under the condition of sandy water irrigation. (Figure 7) At the same time, from the verification results, the prediction accuracy of the E2 (drip tape with inner flat emitter) was high (FE 6–8). However, the prediction accuracy of long channel emitters was low (FE 19–21). Therefore, it is recommended to use this model to predict the performance of short channel ($L < 50$ mm) emitters.

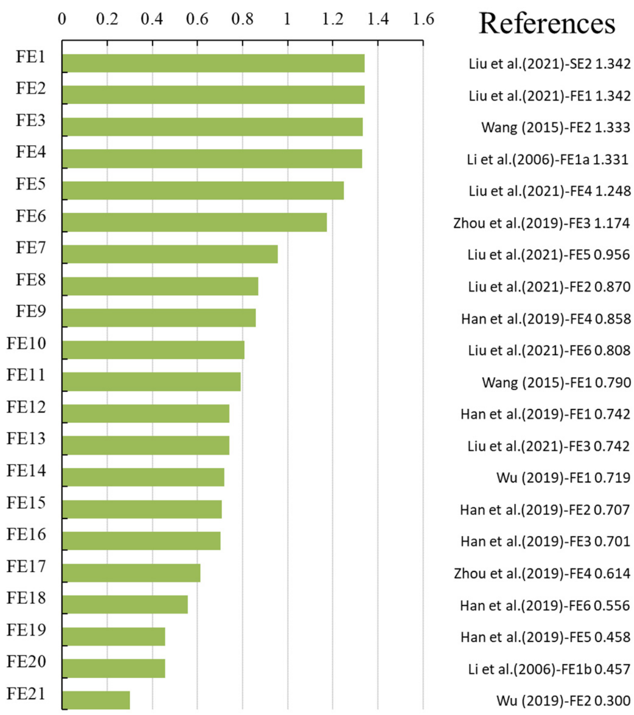

Figure 7. Validation and ranking of available emitters in published papers with predictive models. Note: The figure on the right is the ratio of the calculated actual irrigation life to the results obtained in the paper, which is accurate. "References" and the symbol after the mark are the emitters used in the study. **Data from References** [12,29–35].

Although some meaningful results have been produced, some problems still need to be studied in the future: (1) the relationship between the regression coefficient of characteristic structural parameters in the prediction model, the type of emitters, and irrigation water source conditions; (2) the application feasibility and the consistency of the prediction model in farmland need to be further verified.

5. Conclusions

Considering the indexes (average relative flow, irrigation uniformity), the anti-clogging ability and operation performance of the emitters can be reflected. By comparing the relative average flow and irrigation uniformity under nine kinds of agricultural irrigation water, the individual effects and the comprehensive effects were analyzed. It is proved that it is too optimistic to consider only the irrigation duration based on average relative flow as the criterion to determine the service duration of the emitter. So ESD was proposed to measure the service duration of emitters comprehensively and provide the reference for performance prediction under different water sources. The ESD and the structural characteristic parameters were analyzed, and the sediment particle size and characteristic parameters which have a great influence on the blockage were obtained. It was believed that W/D and $A^{1/2}/L$ were significantly correlated with ESD. The prediction model based on them can directly estimate the service duration of the emitter, and the accuracy can reach 86% after verification, which is suitable for the short channel emitter. The ESD defined in this paper can be used to predict the service life of emitters under different sand-laden water sources, and to select the appropriate emitter to maintain the efficiency, safety, and sustainability of the drip irrigation system.

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