Using an anti-clogging relative index (CRI) to assess emitters rapidly for drip irrigation systems with multiple low-quality water sources

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Abstract: Drip irrigation is considered as one of the most suitable methods to utilize multiple low-quality water sources. However, the emitter clogging issue caused has become the main constraint for its application and promotion, which possibly leads to system failure if it becomes uncontrollably acute. How to select the anti-clogging emitter product precisely, in order to improve the system functionality and extend the service life, is the premise of increasing the sustainability of drip irrigation systems broadly used for agriculture and landscape irrigation. Therefore, drip irrigation emitter clogging experiments using three types of low-quality water sources (including water with high sediment and salinity loads and their mixture with the same volume ratio) were conducted. Under the fourteen working conditions included in the present study, the discharge variation rate (Dra), Christiansen coefficient of uniformity (CU) and emitter clogging substances (ECS) of the referenced emitter all showed linear corrections with the other eight types of emitters used in this paper, and the regression slopes were referred to as the anti-clogging relative index (CRI). The relative magnitudes of CRI_Dra, CRI_CU and CRI_ECS could effectively represent the anti-clogging abilities of different emitters. Instead of being affected by the different working conditions or water quality parameters, the differences in CRI were mainly due to the emitter structural characteristics. Two dimensionless parameters of emitter flow paths (W/D and $A^{1/2}/L$) were significantly correlated to the relative magnitudes of CRI, and thus these two parameters directly allowed for assessing of the anti-clogging ability of emitters. The model established could provide an accurate method for the selection of anti-clogging drip emitter products in a rapid way, which is beneficial for the safe, high-efficiency and long-time running of the drip irrigation system using low-quality water sources.

Key words: low-quality water irrigation; drip irrigation; emitter clogging; direct evaluation

1 Introduction

Utilizing low-quality water sources (such as reclaimed water and other water sources with high sediment and salinity loads) in agricultural irrigation has offered an effective way to address water shortage (Liu and Huang, 2009; Puig-Bargués et al., 2010). However, the excessive or inappropriate use of low-quality water sources may bring about soil and environmental pollution, or even risks to crop safety and human health. Drip irrigation is considered as the most reliable and environmentally friendly method to utilize low-quality water sources, due to its enclosed pipelines, targeted water and fertilizer supply, and controllable outflow (Capra and Scicolone, 2007; Zhou et al., 2013; Lu et al., 2016; Zhangzhong et al., 2016; Han et al., 2018). However, the emitter clogging issue has always been the main barrier to the scaled application and promotion of drip irrigation technology, since it directly affects system operation and service life (Pei et al., 2014; Zhou et al., 2016a). In addition, there are more substances included in low-quality water sources, and their compounds would couple with the reactive components of the fertilizers, which further increases the clogging risk of drip irrigation system, or even leads to system failure.

Selecting the most appropriate emitter product with high anti-clogging ability is critical to improve the drip irrigation system functionality and extend its service life. This would also avoid frequent replacement of the irrigation equipment and the possible wastes related, increasing the sustainability of these systems broadly used for agriculture and landscape irrigation. Therefore, effectively controlling drip irrigation clogging is the key to achieve high-efficiency production when utilizing low-quality water in irrigation. However, emitter design recommendations for avoiding clogging differ between studies. Thus, less clogging was observed with emitters with large outflow or flow path dimensions (Zheng, 1993), emitters with short and wide flow path (Adin and Sacks, 1991), emitters with large cross-sectional average velocities (Feng et al., 2018). Meanwhile, the clogging features were influenced by the water quality characteristics (Zhangzhong et al., 2016; Zhou et al., 2016a). Therefore, the anti-clogging ability of emitters cannot merely be evaluated by the relative magnitudes of rated outflows or flow path dimensions, and a rapid method is needed to predict the anti-clogging ability of emitters. In order to accurately evaluate the emitter anti-clogging ability, most scholars carried out drip irrigation emitter clogging experiments to monitor the dynamic outflow variations of different types of emitters for a long irrigation period (Pei et al., 2014; Bounoua et al., 2016; Han et al., 2018). However, these experiments were time and labor consuming. Although Zhou et al. (2016a) proposed an evaluation method for assessing the emitter anti-clogging ability in a drip irrigation system using reclaimed water, which was based on the characteristic parameters of emitter flow path, there were obvious differences in evaluations for different water sources and different types of emitters. There are still no evaluation and prediction methods for emitter anti-clogging ability which are suitable for various low-quality water qualities and working conditions (such as operating according to irrigation amount or time duration, different working pressures or irrigation frequencies).

The objectives of this paper were to: (1) establish an anti-clogging relative index (CRI) for evaluating anti-clogging ability, and verify its applicability under different low-quality water sources and working conditions; (2) explore the direct prediction method of CRI, based on utilizing characteristic parameters of emitter flow path, as the reference to select appropriate emitters for sustainable drip irrigation systems using low-quality water sources.

2 Material and Methods

2.1 Experiment layout

The drip irrigation emitter clogging experiments were carried out both in 2015 and 2017 at the irrigation experimental station located at Ulanbuhe arid area in Bayinaoer, Inner Mongolia, China (106.98° E, 40.39° N). There were three types of low-quality water sources: the high-sediment water imported from the Yellow River (YRW), the brackish water brought from the local lake (SLW), and their 1:1 mixed water in volume as the mixed water source (MXW). Waters were sampled seven times in 2015 and six times in 2017 to determine the main quality parameters that are shown in Table 1.

<# Table 1 approximately here #>

There were fourteen different working conditions included in the experiments, and they were either based on the total operation time control (named as TOTC) or the total emitter discharge control (named as TEDC). Among them, the TOTC scenarios were mainly focused on the low-quality water sources, including three water sources with flushing treatments, as well as the non-flushing treatment of YRW. On the other hand, the TEDC scenarios were the fertigation treatments, including applying the urea phosphate (named as UP) with two concentrations (0.15 g/L and 0.30 g/L, which were designated as UP0.15 and UP0.30, respectively), the potassium phosphate monobasic (named as PPM) with two concentrations (0.15 g/L and 0.30 g/L, which were designated as PPM0.15 and PPM0.30, respectively), the ammonium polyphosphate (named as APP) with two concentrations (0.15 g/L and 0.30 g/L, which were named as APP0.15 and APP0.30, respectively), and the control group without fertilizers, as well as three irrigation frequencies with PPM0.15 (irrigate once every day, four days and seven days, which were named as P1/1, P1/4 and P1/7, respectively). The fourteen working conditions are summarized in Table 2.

<# Table 2 approximately here #>

Nine types of emitters (those that were used in at least four working conditions among the total fourteen scenarios mentioned above) were selected to further analyze their anti-clogging abilities under different water sources and working conditions. The geometric parameters of emitter flow path were quantified using a reading microscope (type: JC-10; range: <4 mm; measurement accuracy: ±0.01 mm; manufacturer: SHOIF, Shanghai, China) and a digital vernier caliper (type: PD-151; range: <150 mm; measurement accuracy: ±0.02 mm; manufacturer: Pro's Kit, Taiwan, China). The initial outflow was measured with the preliminary experiment and their manufacturing variation coefficients were obtained from the manufacturers. These results are summarized in Table 3.

<# Table 3 approximately here #>

2.2 Testing methods for drip irrigation emitter clogging parameters and substances

(1) Emitter outflow indices

The emitter outflow was tested during 5 min every 60 h (for TOTC scenarios) or every 8 days (for TEDC scenarios) of system operation. These scenarios operated with consistent time every day till the clogging degree reached 50%, which happened between 1 and 4 months depending on the operation modes summarized in Table 2. The data obtained were corrected by the temperature modification model used by Zhou et al. (2018) to eliminate the effects of temperature differences. Then the revised outflow results were used to calculate the average discharge variation rate (Dra) to reflect the overall clogging condition of the drip irrigation system, and meanwhile the irrigation uniformity was characterized by the Christiansen coefficient of uniformity (CU). The calculation methods were introduced in Zhou et al. (2018).

(2) Clogging substances

The clogging substances inside each type of emitter (ECS) were extracted and tested when the Dra was decreased to 95%, 90%, 85%, 80%, 75%, 70%, 60% and 50%, respectively. Five emitters were collected from the head, middle and end sections of the laterals, respectively, and then were weighed with an electronic balance (type: 2204 N; measurement accuracy: 10^{-4} g; manufacturer: Benpu, Suzhou, China). Emitter samples were removed from the laterals and placed in a valve bag with 45 mL deionized water. Then each bag was placed in an ultrasonic cleaner (type: GVS-10L; manufacturer: Gouwei Technology Co. Ltd., Shenzhen, China) for 60 min at 60 Hz to strip off the clogging substances. The emitter samples were dried in an oven at a constant temperature of 110°C and then weighed again. The weight difference was the content of ECS, and the average value is presented for the fifteen emitters.

2.3 Anti-clogging relative index (CRI)

In order to comprehensively assess the anti-clogging ability of emitters under different working conditions, the concept of the anti-clogging relative index (CRI) is proposed. CRI could cover the all main parameters of emitter clogging (Dra, CU and ECS) introduced in the previous section. The initial values (i.e. without emitter clogging) for Dra, CU and ECS should be100%, 100% and 0 $mg \cdot cm^{-2}$, respectively. By using CRI, one type of emitter was taken as the reference, and its performance difference with other types of emitters was quantified by the ratio of their anti-clogging parameters:

$$\mathrm{CRI} = \frac{EI_i}{EI_0} \qquad (1)$$

where:

EI_i—the clogging parameter (Dra, CU or ECS) of the i^{th} emitter studied. The units for Dra and CU are %, and that of ECS is mg·cm^{-2};

EI_0—the clogging parameter of the reference emitter, being the parameters and their units the same as EI_i. The reference emitter could be any commercial product. Flat emitter FE1 was selected in this paper mainly because it was used in all fourteen working conditions;

CRI—the anti-clogging relative index, which indicated the relative magnitudes of anti-clogging comparing to the reference emitter. The results were the linear regression slopes of EI_i and EI_0. Larger CRI means higher anti-clogging ability.

2.4 Statistical analysis

Linear regression analysis was used to quantify the correlations among clogging parameters (Dra, CU and ECS). For the initial conditions, the emitters were considered ideally unclogged (Dra=CU=100%) without any clogging substances (ECS=0 mg·cm^{-2}). Therefore, the regression lines included dot (100%, 100%) for both Dra and CU correlations, while those for ECS included dot (0, 0). Then the same analysis method was further applied to study the correlations between CRI (CRI_Dra, CRI_CU and CRI_ECS) and structural parameters, including emitter initial outflow (Q), flow path length (L), width (W), depth (D), cross sectional area (A, which equals to $W\times D$), average cross-section velocity (v, which equals to Q/A) as well as two dimensionless ratios between emitter flow path width and depth (W/D) and cross sectional area and length ($A^{1/2}/L$) (Li et al., 2018).

Following statistical analyses, the significance of the independent variable was determined at $p<0.05$. The statistical analyses were carried out using SPSS (ver. 20.0, IBM Analytics) software.

3 Results

3.1 Evaluation of emitter performance based on the overall clogging degree (CRI_Dra)

Fig. 1 shows the quantitative correlations of Dra among nine types of emitters and the CRI_Dra obtained accordingly.

Under the fourteen working conditions included in the experiments, Dra of emitters FE2-FE9 showed a linear distribution with that of the reference emitter (FE1). The differences in water sources and working conditions merely changed the position around the regression line, rather than affecting the overall distribution. All the Dra of FE2-FE9 had significant linear correlations with the Dra of FE1 (R^2>0.96, p<0.05). Through the slopes of regression curves, the CRI_Dra of FE2-FE9 were obtained as 0.99, 1.14, 1.06, 0.95, 1.01, 1.20, 0.89 and 0.80, respectively. Since the manufacturing variation coefficients of all types of emitters were similar (Table 3), the differences in CRI_Dra mainly resulted from their anti-clogging performances. The results also indicated that, under all water sources and working conditions, emitter FE7 showed the best anti-clogging ability, which was 20% stronger than the reference FE1; while that of emitter FE9 was on average 20% weaker than FE1. Therefore, on the basis of the evaluation of the CRI_Dra, FE3, FE4 and FE7 all had better anti-clogging ability than FE1, as their CRI_Dra were relatively larger. Meanwhile, FE2 and FE6 anti-clogging capacity were almost the same as FE1, and the other three types of emitters showed relatively weaker anti-clogging ability than FE1.

<# Fig. 1 approximately here #>

3.2 Evaluation of emitter performance based on the irrigation uniformity (CRI_CU)

Fig. 2 shows the quantitative correlations of CU among nine types of emitters and the CRI_CU obtained accordingly.

Linear corrections for CU were also obtained, which showed consistency with those of their Dra. The differences in the relative positions of each emitter were due to different water sources and working conditions. The CU of FE2-FE9 showed significant linear correlations with the CU of FE1 (R^2>0.94, p<0.05), and the CRI_CU of emitters FE2-FE9 were acquired with the regression slopes, being 1.03, 1.19, 1.09, 0.94, 1.01, 1.26, 0.98 and 0.85, respectively. Based on the evaluation results of CRI_CU, FE3, FE4 and FE7 had better anti-clogging ability than FE1, while FE2, FE6 and FE8 had almost the same. The other two types of emitters (FE5 and FE9) showed relatively weaker anti-clogging ability than FE1. The ranking of CRI_CU was slightly different from that of CRI_Dra. However, the common ground lies in the maximum CRI_CU (1.26) obtained by emitter FE7 and the minimum CRI_CU (0.85) by emitter FE9.

<# Fig. 2 approximately here #>

3.3 Evaluation of emitter performance based on the clogging substances (CRI_ECS)

Fig. 3 shows the quantitative correlations of ECS among nine types of emitters and the CRI_ECS obtained accordingly. The ECS of emitters FE2-FE9 showed significant linear correlations with the ECS of FE1 (R^2>0.93, p<0.05). Slopes of the fitted curves for FE2-FE9 were respectively 1.10, 1.15, 1.11, 1.02, 1.09, 0.96, 0.81 and 0.95. Therefore, the anti-clogging abilities of FE2, FE3, FE4 and FE6 were better than FE1 on basis of the CRI_ECS evaluation. FE5 and FE7 showed similar anti-clogging ability comparing with FE1, and those of FE8 and FE9 were relatively weaker. The ranking order of the CRI_ECS results was different from those of the CRI_Dra and CRI_CU. Under this condition, FE3 had the relatively highest CRI_ECS (1.15) while FE8 showed the lowest (0.81).

<# Fig. 3 approximately here #>

4 Discussion

Selecting the appropriate drip irrigation emitters, which are suitable for different working conditions, is of vital importance to avoid emitter clogging when using low-quality water sources. In addition, frequent replacement of the irrigation equipment due to emitter clogging may lead to concomitant secondary pollution. In order to select the most suitable emitter products accurately, scholars in related studies explored and came up with several parameters to reflect emitter performance, including flow index (x), Dra, CU*,* design uniformity coefficient (DU) and statistic uniformity (Us) (Wei et al., 2008; Zhang et al., 2011; Feng et al., 2018). These parameters were obtained through either short-cycle rapid tests or long-cycle dynamic monitoring tests. However, these tests could not comprehensively evaluate the anti-clogging performance because they were carried out with specific types of water source or working condition. Under these circumstances, it was only possible to assess the anti-clogging ability under each specific experimental condition but could not select the appropriate emitters rapidly and accurately for different low-quality water sources or working conditions.

4.1 Selection of the reference emitter

In this paper, three types of low-quality water sources applied under fourteen working conditions were included for the drip irrigation experiments, and the CRI was proposed as an easy index for computing emitter performance against clogging. Taking CRI of the reference emitter FE1 as 1, the CRI values of the other eight types of emitters were obtained with linear regression, and thus relative magnitudes of CRI_Dra, CRI_CU and CRI_ECS could well represent the specific anti-clogging ability of each emitter.

One advantage of the CRI index is that any commercial emitter product could be used as the reference emitter. In this paper, FE1 was selected mainly because it was used in all 14 working conditions. However, the effect of the selected reference emitter on CRI should be assessed. Considering that at least one shared working condition was needed for comparison, FE6 was firstly regarded as another reference emitter, and the CRI_Dra results and rankings of different emitter products are summarized in Table 4. Although the CRI_Dra values changed with the new reference emitter, their overall ranking was almost the same. The slightly inconsistency among FE1, FE2 and FE5 was mainly because their CRI_Dra values were close to each other, which indicated their anti-clogging abilities were almost the same. But the largest CRI_Dra was still obtained with FE7, and the smallest CRI_Dra was acquired by FE9.

Both FE1 and FE6 showed similar CRI_Dra values when FE1 was selected as the reference emitter, which may be the reason for the consistent results obtained above. Therefore, we further selected the emitters with relatively larger (FE3, 1.14) and smaller (FE9, 0.80) CRI_Dra values. According to the results obtained in Table 4, they both showed the same ranking of CRI_Dra values of the emitter products included, and thus verified the consistency of selecting different types of emitters for calculating CRI.

<# Table 4 approximately here #>

4.2 Direct estimation method of CRI based on their structural parameters

The correlations between CRI values and the structural parameters of the emitter flow path (including Q, L, W, D, v; $A^{1/2}/L$ and W/D) were also analyzed using linear regressions. Only W/D and $A^{1/2}/L$ showed significant linear correlations with all three CRI parameters (R^2>0.42, p<0.05, Fig. 4). This explained why neither larger outflow and flow path (Zheng, 1993), short flow path (Adin and Sacks, 1991) nor larger average cross-sectional velocity (Feng et al., 2018) were the best choice, as these references for selecting the appropriate emitter products were obtained from either fixed water source or specific working condition. This was exactly the starting point of the study in this paper.

In this study, the two dimensionless parameters (*W/D* and $A^{1/2}/L$) acquired were the combination of the fundamental structural parameters (*L*, *W*, *D*), and their joint effects led to the variations of local hydrodynamics inside emitters (Feng et al., 2018). As a result, the local hydrodynamics changed the dynamic "attach-detach-regrow" process of the clogging substances, and correspondingly their accumulation (Zhangzhong et al., 2016; Zhou et al., 2016b). As accumulated clogging substances directly affected the emitter clogging degrees (Zhou et al., 2013), the service life and application benefit of the drip irrigation systems using low-quality water sources varied accordingly.

<# Fig. 4 approximately here #>

As *W/D* was not significantly correlated to $A^{1/2}/L$ (r= 0.55; significance value=0.128; sample number=9), the variations of CRI were merely determined by *W/D* and $A^{1/2}/L$ of different types of emitters. Therefore, multiple-linear correlations were established for CRI_Dra, CRI_CU and CRI_ECS, respectively. According to the Equations 2-4 and statistical results obtained, CRI_Dra was the most suitable parameter to evaluate the anti-clogging ability of emitters as it contributed the largest regression coefficient while their RMSE values were almost the same.

$$CRI\_Dra=-13.16\times A^{1/2}/L-0.33\times W/D+1.57 \quad (R^2=0.75, \text{RMSE}=0.06, \text{F}=20.99, p<0.05) \qquad (2)$$

$$CRI\_CU=-14.48\times A^{1/2}/L-0.25\times W/D+1.55 \quad (R^2=0.62, \text{RMSE}=0.07, \text{F}=11.44, p<0.05) \qquad (3)$$

$$CRI\_ECS=-11.26\times A^{1/2}/L-0.24\times W/D+1.46 \quad (R^2=0.62, \text{RMSE}=0.06, \text{F}=11.46, p<0.05) \qquad (4)$$

4.3 The feasibility and accuracy of utilizing CRI to select commercial product

In order to verify the feasibility and accuracy of the CRI method proposed, we collected data from all the emitter clogging related papers available. By doing so, we could apply the estimation model established in the previous section to further verify its accuracy to evaluate the anti-clogging abilities of the various emitters studied under the other working conditions described in these papers. Unfortunately, the majority of the studies did not report all of the structural parameters of the flat emitters used. Eventually, we summarized twenty-eight types of emitters in total, and the results indicated that the accuracy of CRI_Dra exceeded 86%, which means that twenty-four of the emitters (those marked in black in Fig. 5) showed consistency with the results in the studies (. E28 showed the lowest CRI_Dra as its flow path width was relatively large (1.68 mm) while flow path depth was relatively small (0.48 mm), and the CRI_Dra showed negative linear correlation with *W/D* (Equation 2). Results demonstrated that the accuracy of the CRI method was suitable for selecting the most appropriate emitter products against clogging for drip irrigation systems using low-quality water sources.

<# Fig. 5 approximately here #>

Although some meaningful results were obtained based on the establishment and the verification of the CRI models, some issues still need to be studied in the future: (1) the estimation models were obtained with flat emitters and the regression coefficients for *W/D* and $A^{1/2}/L$ for other types of emitters needs to be verified; (2) the feasibility and consistency of drip irrigation systems using low-quality water sources applied under farm conditions requires further verification.

5 Conclusion

By systematic study and analysis of the drip irrigation emitter outflows under fourteen working conditions using low-quality water sources with high sediment and salinity loads for agricultural irrigation, the anti-clogging relative index (CRI) was proposed to assess the anti-clogging ability of each emitter. Considering the clogging related parameters (the average discharge variation rate, Dra; and the Christiansen coefficient of uniformity, CU) and clogging substances found inside emitters (ECS), the relative magnitudes of CRI_Dra, CRI_CU and CRI_ECS could effectively represent the relative differences of anti-clogging abilities of the tested emitters. CRI results were accurate and consistent under all water sources and working conditions. Their differences were determined by their structural characteristics, rather than the water used or the operating mode. The dimensionless ratios between emitter flow path width and depth (*W/D)* and cross sectional area and length ($A^{1/2}/L$) were significantly correlated to CRI, especially CRI_Dra, and the estimation model established on basis of *W/D* and $A^{1/2}/L$ could be utilized to directly predict emitter anti-clogging ability. The CRI index here defined is useful for selecting the suitable emitters for drip irrigation systems with low-quality water sources to maintain its high-efficiency, safe operation and sustainability.

Acknowledgements

We are grateful for the financial support from the National Key Research Project (2017YFD0201504), and the National Natural Science Fund of China (51790531, 51479197, 51621061).

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Captions for Figures and Tables in the Paper

Fig. 1 Regression and coefficient of determination for Dra between different types of emitters

Fig. 2 Regression and coefficient of determination for CU between different types of emitters

Fig. 3 Regression and coefficient of determination for ECS between different types of emitters

Fig. 4 Coefficient of determination between the anti-clogging relative index and two dimensionless parameters of emitter flow path

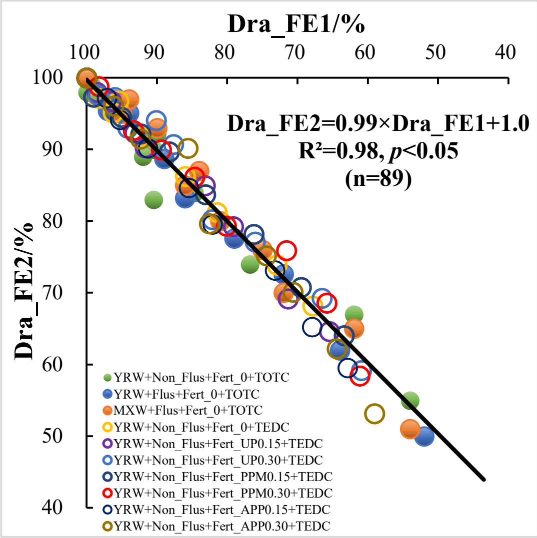
Fig. 5 Verification and ranking of the flat emitters available in published papers using CRI_Dra

Table 1 Ranges of the water quality parameters tested

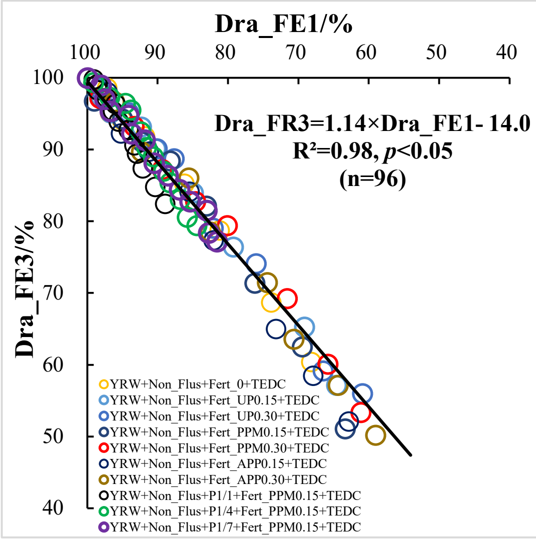
Table 2 Treatments and working conditions included in the experiments

Table 3 Manufacturing and geometric parameters emitters used in the experiments

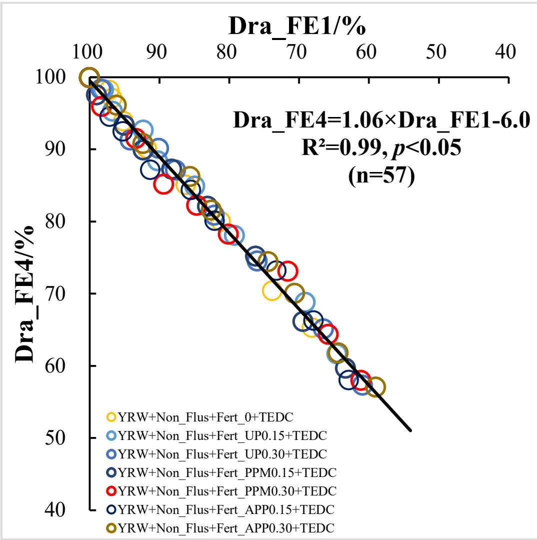
Table 4 Consistency of anti-clogging ability with different reference emitters for CRI_Dra calculation


Dra_FE1/%
Dra_FE2/%
Dra_FE2=0.99×Dra_FE1+1.0
R²=0.98, p<0.05
(n=89)
YRW+Non_Flus+Fert_0+TOTC
YRW+Flus+Fert_0+TOTC
MXW+Flus+Fert_0+TOTC
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_UP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC

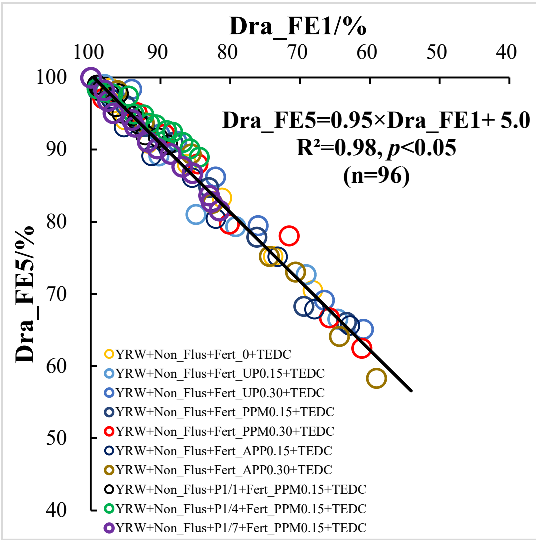
(a)


Dra_FE1/%
Dra_FE3/%
Dra_FR3=1.14×Dra_FE1- 14.0
R²=0.98, p<0.05
(n=96)
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_UP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC
YRW+Non_Flus+P1/1+Fert_PPM0.15+TEDC
YRW+Non_Flus+P1/4+Fert_PPM0.15+TEDC
YRW+Non_Flus+P1/7+Fert_PPM0.15+TEDC

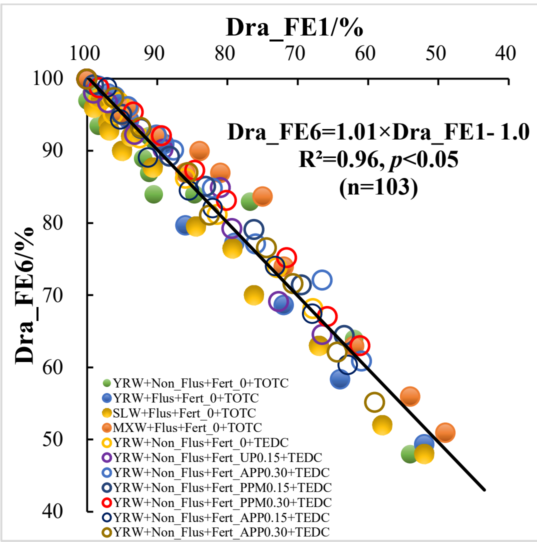
(b)


Dra_FE1/%
Dra_FE4/%
Dra_FE4=1.06×Dra_FE1-6.0
R²=0.99, p<0.05
(n=57)
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_UP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC

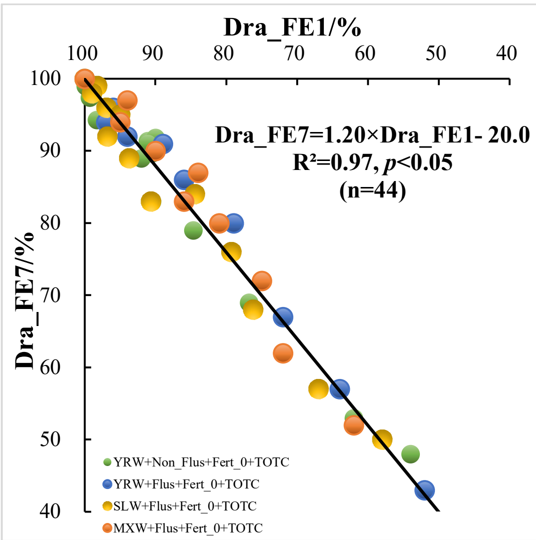
(c)


Dra_FE1/%
Dra_FE5/%
Dra_FE5=0.95×Dra_FE1+ 5.0
R²=0.98, p<0.05
(n=96)
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_UP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC
YRW+Non_Flus+P1/1+Fert_PPM0.15+TEDC
YRW+Non_Flus+P1/4+Fert_PPM0.15+TEDC
YRW+Non_Flus+P1/7+Fert_PPM0.15+TEDC

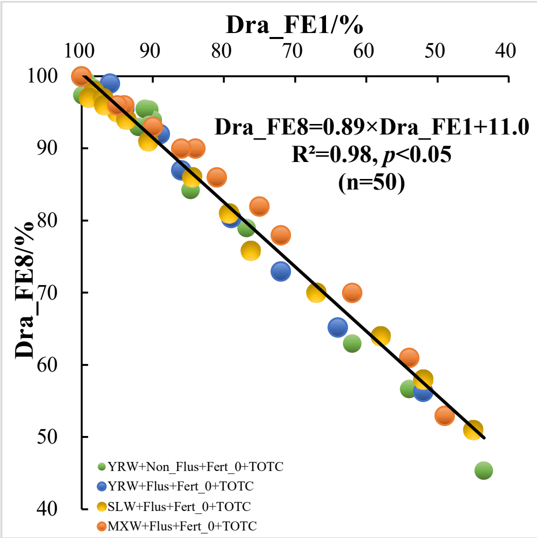
(d)


Dra_FE1/%
Dra_FE6/%
Dra_FE6=1.01×Dra_FE1- 1.0
R²=0.96, p<0.05
(n=103)
YRW+Non_Flus+Fert_0+TOTC
YRW+Flus+Fert_0+TOTC
SLW+Flus+Fert_0+TOTC
MXW+Flus+Fert_0+TOTC
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC

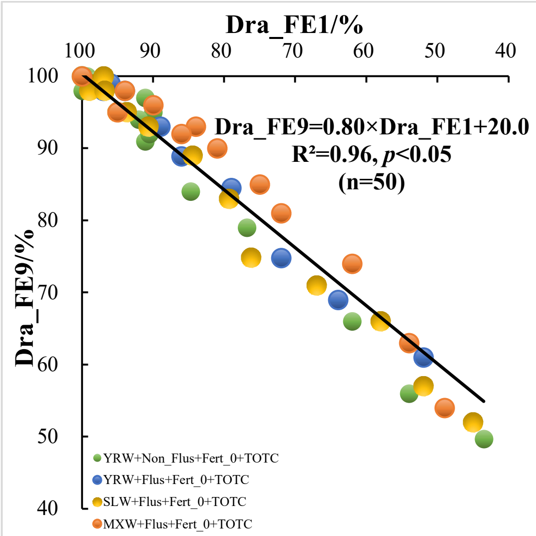
(e)


Dra_FE1/%
Dra_FE7/%
Dra_FE7=1.20×Dra_FE1- 20.0
R²=0.97, p<0.05
(n=44)
YRW+Non_Flus+Fert_0+TOTC
YRW+Flus+Fert_0+TOTC
SLW+Flus+Fert_0+TOTC
MXW+Flus+Fert_0+TOTC

(f)



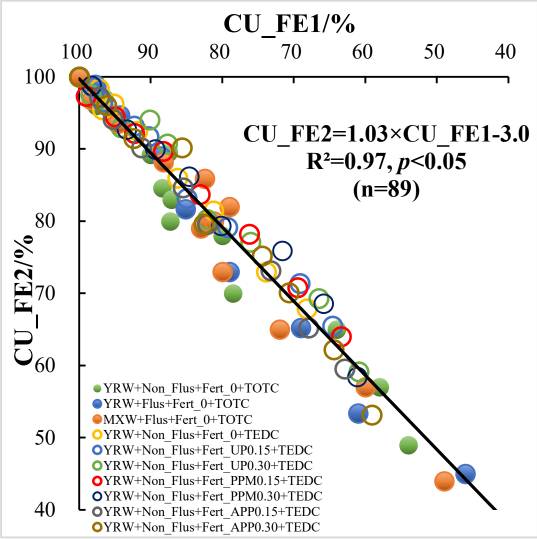
(g)



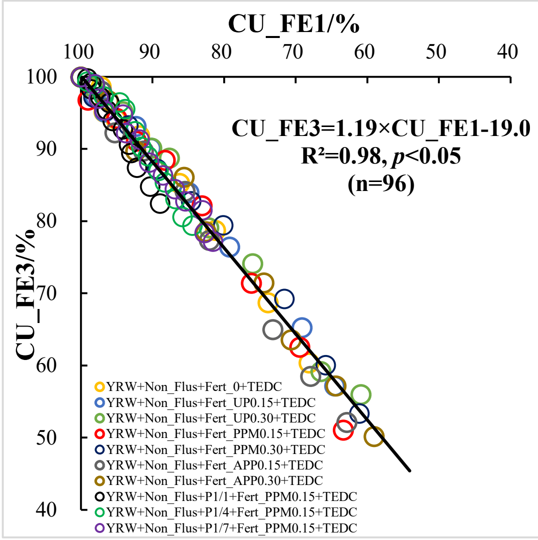
(h)

Fig. 1 Regression and coefficient of determination for Dra between different types of emitters[a]

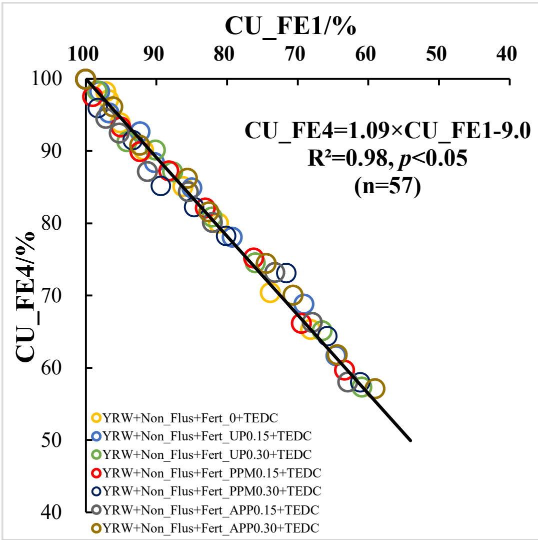
[a] Dra was the average discharge variation rate; Dra_FE*i* was the Dra of the *i*th emitters those applied in the experiments and summarized in Table 3; $p<0.05$ indicated the regression results reached the significant level at the confidence interval of 95%; n indicated the total number of sampling points included; CRI_Dra was the anti-clogging relative index based on Dra.


CU_FE1/%
CU_FE2/%
CU_FE2=1.03×CU_FE1-3.0
R²=0.97, p<0.05
(n=89)
YRW+Non_Flus+Fert_0+TOTC
YRW+Flus+Fert_0+TOTC
MXW+Flus+Fert_0+TOTC
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_UP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC

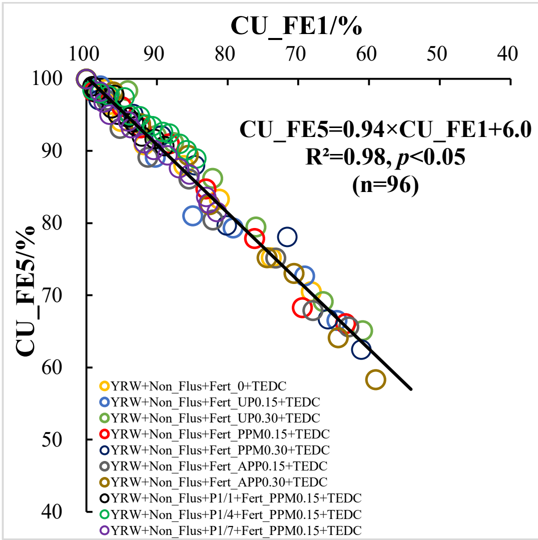
(a)


CU_FE1/%
CU_FE3/%
CU_FE3=1.19×CU_FE1-19.0
R²=0.98, p<0.05
(n=96)
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_UP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC
YRW+Non_Flus+P1/1+Fert_PPM0.15+TEDC
YRW+Non_Flus+P1/4+Fert_PPM0.15+TEDC
YRW+Non_Flus+P1/7+Fert_PPM0.15+TEDC

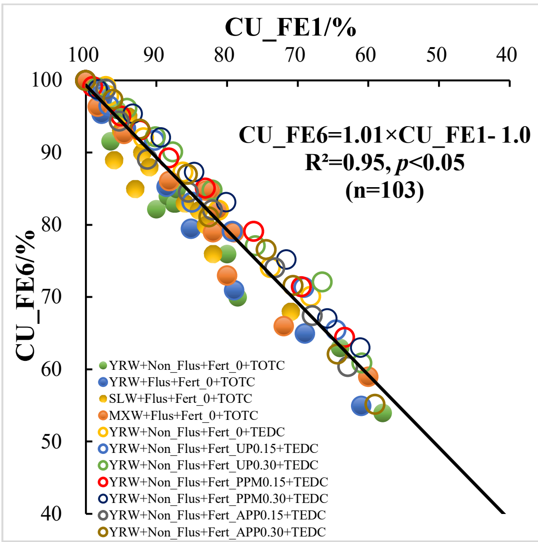
(b)


CU_FE1/%
CU_FE4/%
CU_FE4=1.09×CU_FE1-9.0
R²=0.98, p<0.05
(n=57)
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_UP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC

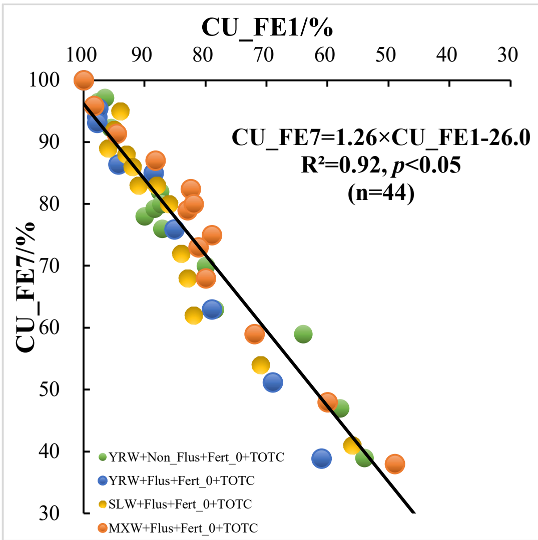
(c)


CU_FE1/%
CU_FE5/%
CU_FE5=0.94×CU_FE1+6.0
R²=0.98, p<0.05
(n=96)
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_UP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC
YRW+Non_Flus+P1/1+Fert_PPM0.15+TEDC
YRW+Non_Flus+P1/4+Fert_PPM0.15+TEDC
YRW+Non_Flus+P1/7+Fert_PPM0.15+TEDC

(d)


CU_FE1/%
CU_FE6/%
CU_FE6=1.01×CU_FE1- 1.0
R²=0.95, p<0.05
(n=103)
YRW+Non_Flus+Fert_0+TOTC
YRW+Flus+Fert_0+TOTC
SLW+Flus+Fert_0+TOTC
MXW+Flus+Fert_0+TOTC
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_UP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC

(e)


CU_FE1/%
CU_FE7/%
CU_FE7=1.26×CU_FE1-26.0
R²=0.92, p<0.05
(n=44)
YRW+Non_Flus+Fert_0+TOTC
YRW+Flus+Fert_0+TOTC
SLW+Flus+Fert_0+TOTC
MXW+Flus+Fert_0+TOTC

(f)

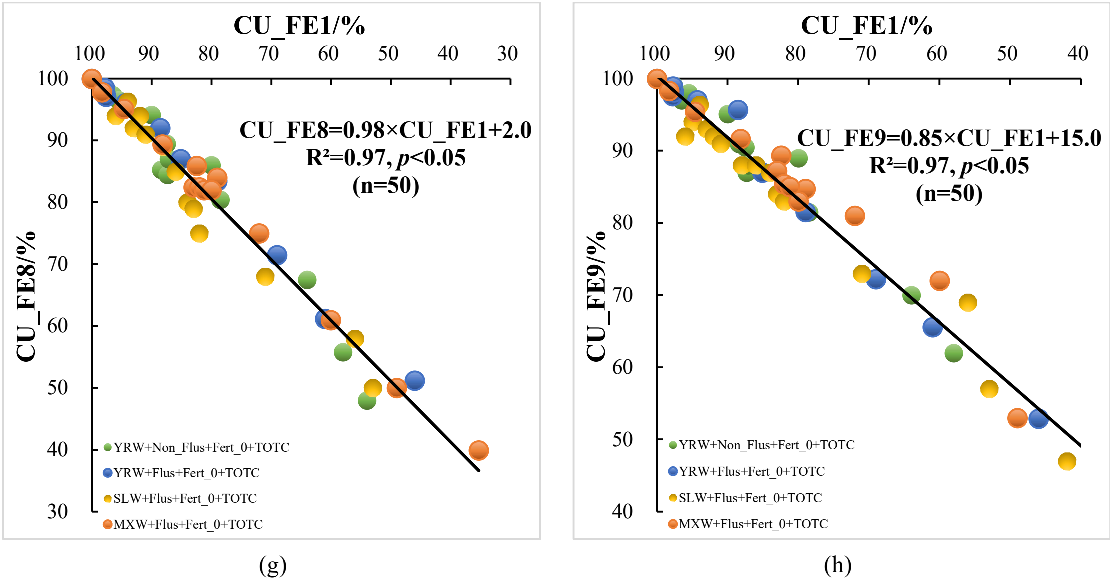
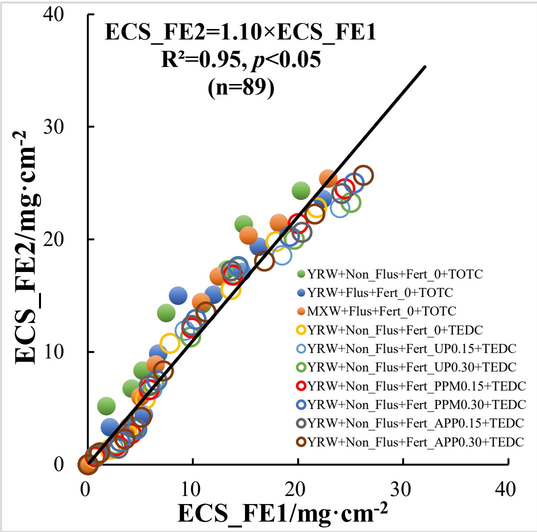
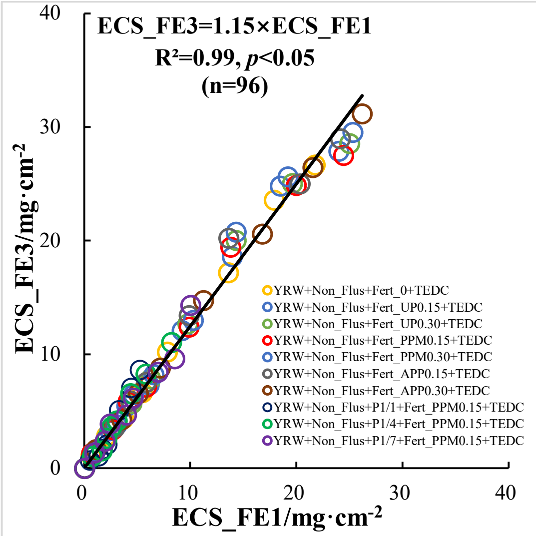


Fig. 2 Regression and coefficient of determination for CU between different types of emitters [a]

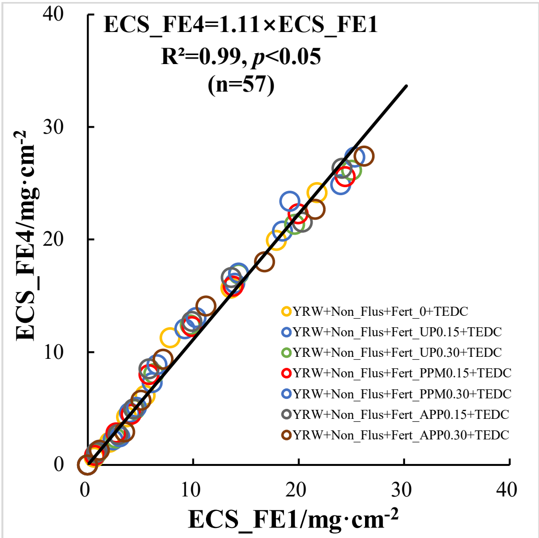
[a] CU was the Christiansen coefficient of uniformity; CU_FE*i* was the CU of the *i*th emitters those applied in the experiments and summarized in Table 3; $p<0.05$ indicated the regression results reached the significant level at the confidence interval of 95%; n indicated the total number of sampling points included; CRI_CU was the anti-clogging relative index based on CU.


ECS_FE2=1.10×ECS_FE1
R²=0.95, p<0.05
(n=89)
ECS_FE2/mg·cm-2
ECS_FE1/mg·cm-2
YRW+Non_Flus+Fert_0+TOTC
YRW+Flus+Fert_0+TOTC
MXW+Flus+Fert_0+TOTC
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_UP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC

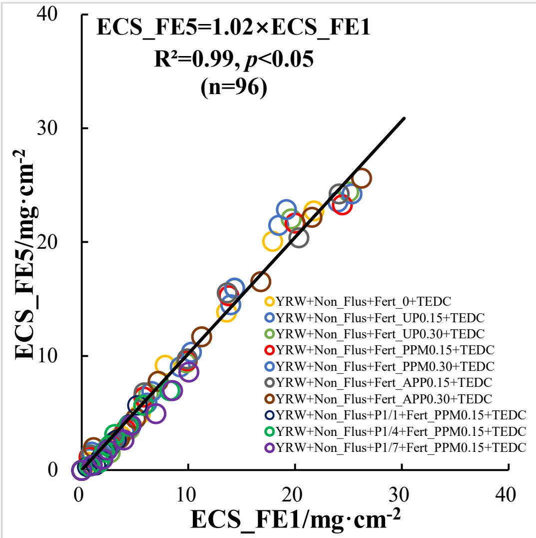
(a)


ECS_FE3=1.15×ECS_FE1
R²=0.99, p<0.05
(n=96)
ECS_FE3/mg·cm-2
ECS_FE1/mg·cm-2
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_UP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC
YRW+Non_Flus+P1/1+Fert_PPM0.15+TEDC
YRW+Non_Flus+P1/4+Fert_PPM0.15+TEDC
YRW+Non_Flus+P1/7+Fert_PPM0.15+TEDC

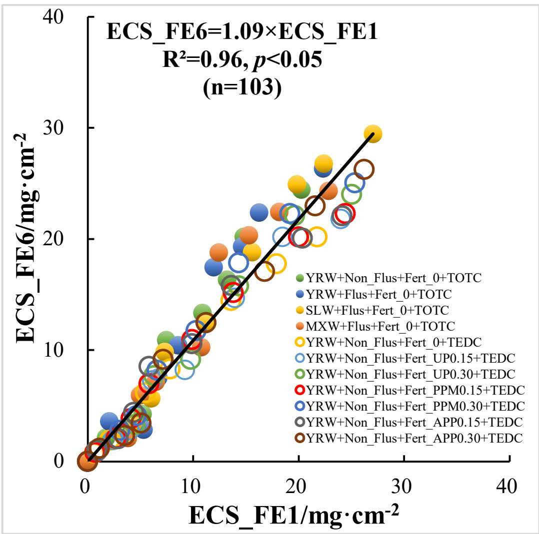
(b)


ECS_FE4=1.11×ECS_FE1
R²=0.99, p<0.05
(n=57)
ECS_FE4/mg·cm-2
ECS_FE1/mg·cm-2
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_UP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC

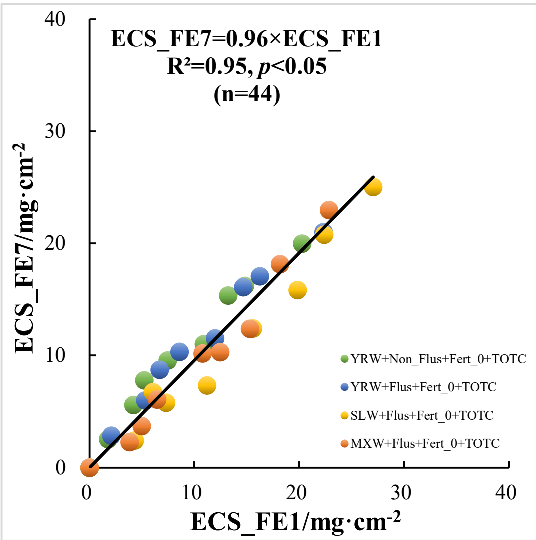
(c)


ECS_FE5=1.02×ECS_FE1
R²=0.99, p<0.05
(n=96)
ECS_FE5/mg·cm-2
ECS_FE1/mg·cm-2
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_UP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC
YRW+Non_Flus+P1/1+Fert_PPM0.15+TEDC
YRW+Non_Flus+P1/4+Fert_PPM0.15+TEDC
YRW+Non_Flus+P1/7+Fert_PPM0.15+TEDC

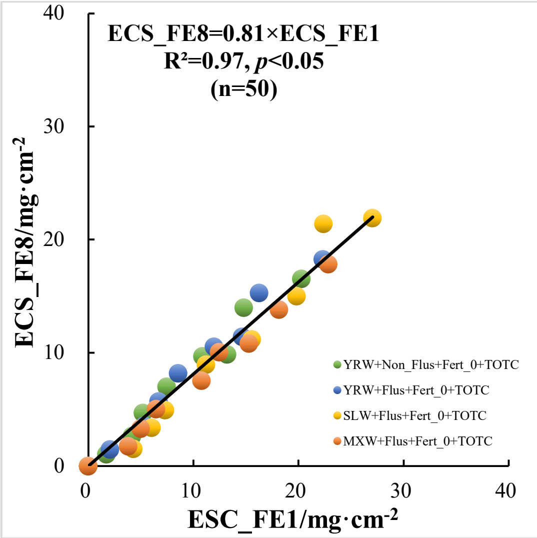
(d)


ECS_FE6=1.09×ECS_FE1
R²=0.96, p<0.05
(n=103)
ECS_FE6/mg·cm-2
ECS_FE1/mg·cm-2
YRW+Non_Flus+Fert_0+TOTC
YRW+Flus+Fert_0+TOTC
SLW+Flus+Fert_0+TOTC
MXW+Flus+Fert_0+TOTC
YRW+Non_Flus+Fert_0+TEDC
YRW+Non_Flus+Fert_UP0.15+TEDC
YRW+Non_Flus+Fert_UP0.30+TEDC
YRW+Non_Flus+Fert_PPM0.15+TEDC
YRW+Non_Flus+Fert_PPM0.30+TEDC
YRW+Non_Flus+Fert_APP0.15+TEDC
YRW+Non_Flus+Fert_APP0.30+TEDC

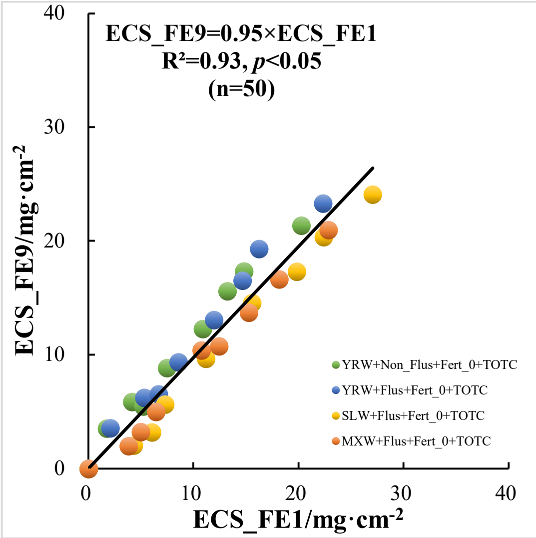
(e)


ECS_FE7=0.96×ECS_FE1
R²=0.95, p<0.05
(n=44)
ECS_FE7/mg·cm-2
ECS_FE1/mg·cm-2
YRW+Non_Flus+Fert_0+TOTC
YRW+Flus+Fert_0+TOTC
SLW+Flus+Fert_0+TOTC
MXW+Flus+Fert_0+TOTC

(f)



(g)



(h)

Fig. 3 Regression and coefficient of determination for ECS between different types of emitters [a]

[a] ECS was the emitter clogging substances; ECS_FE*i* was the ECS of the *i*th emitters those applied in the experiments and summarized in Table 3; $p<0.05$ indicated the regression results reached the significant level at the confidence interval of 95%; n indicated the total number of sampling points included; CRI_ECS was the anti-clogging relative index based on ECS.

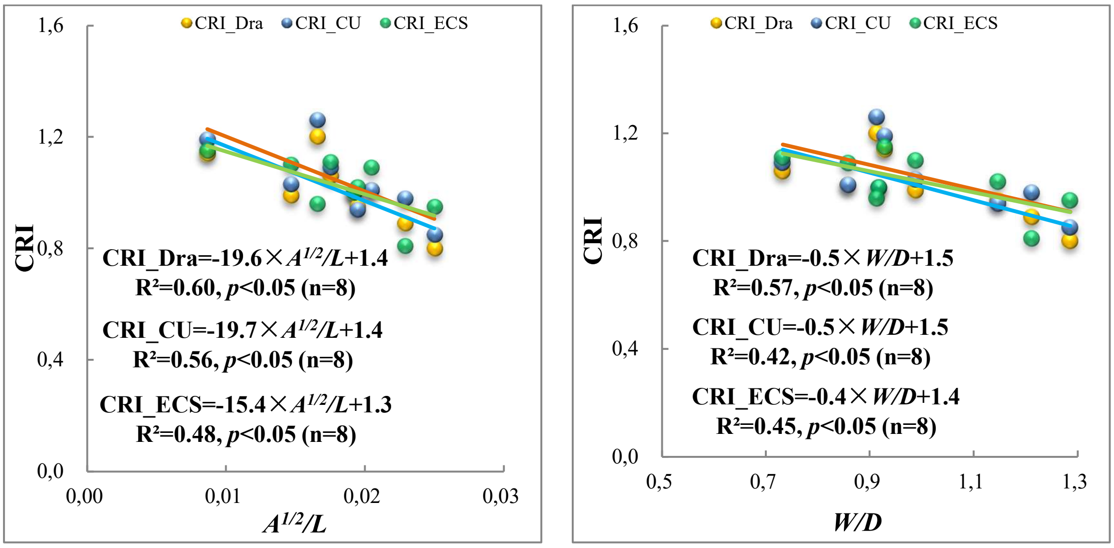


Fig. 4 Coefficient of determination between the anti-clogging relative index and two dimensionless parameters of emitter flow path[a]

[a] CRI_Dra, CRI_CU and CRI_ECS were the anti-clogging relative index based on average discharge variation rate (Dra), Christiansen coefficient of uniformity (CU) and emitter clogging substances (ECS), respectively; L, W and D were the length, width and depth of the emitter flow path; A is the cross sectional area, which equals to $W \times D$; $p<0.05$ indicated the regression results reached the significant level at the confidence interval of 95%; n indicated the total number of sampling points included.

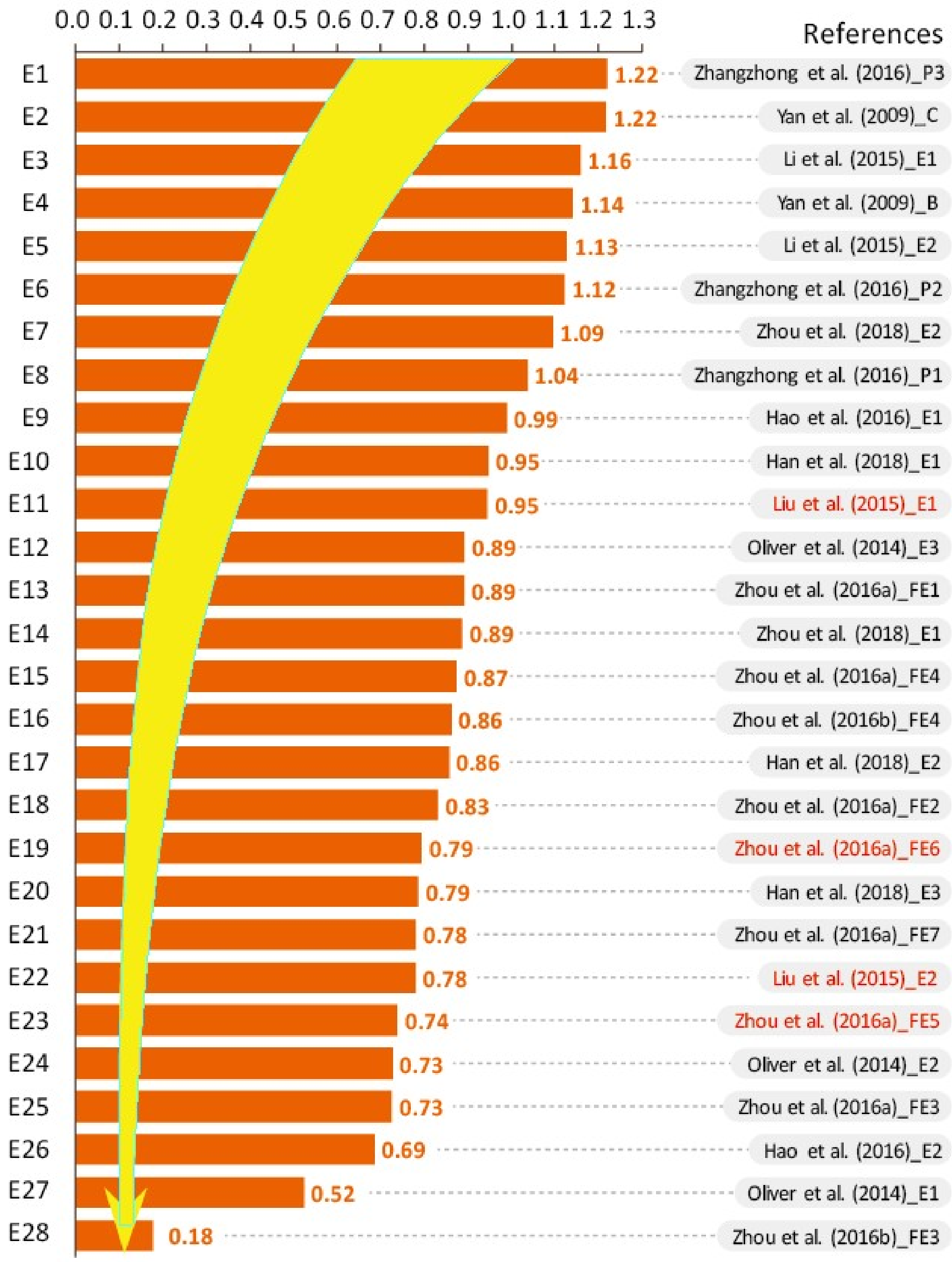


Fig. 5 Verification and ranking of the flat emitters available in published papers using CRI_Dra[a]

[a] The numbers on the right side of the bars were the anti-clogging relative index based on average discharge variation rate (CRI _Dra) calculated; the symbols after the "references" and the "_" mark were the emitters used in the study accordingly; the "references" in black indicated the anti-clogging ability matched the results in journal papers, while those in red were not.

Table 1 Ranges of the water quality parameters tested[a]

Water sources	YRW		SLW	MXW
Experiment year	2017	2015	2015	2015
pH	7.2-7.9	7.5-7.9	8.9-9.2	8.3-8.5
Suspended solids (mg L^{-1})	32.1-50.4	38.1-42.5	<5	26.1-27.8
Electrical conductivity (μs cm^{-1})	781-800	766-7739	9454-9465	6005-6014
Chemical oxygen demand (mg L^{-1})	5.9-7.2	5.9-7.2	15.1-17.5	6.3-6.9
Biochemical oxygen demand (mg L^{-1})	1.5-1.9	1.5-1.9	2.6-2.9	1.5-1.9
Total phosphorus (mg L^{-1})	0.04-0.08	0.04-0.07	0.09-0.12	0.04-0.07
Total nitrogen (mg L^{-1})	1.2-1.7	1.2-1.5	1.6-1.8	1.2-1.5
Ca^{2+} concentration (mg L^{-1})	53.6-55.4	52.7-53.9	320.5-323.7	52.7-53.9
Mg^{2+} concentration (mg L^{-1})	24.2-27.6	23.7-26.1	121.5-125.8	23.7-26.1
PO_4^{3-} concentration (mg L^{-1})	—	0.21-0.29	0.27-0.34	0.24-0.31
CO_3^{2-}+HCO_3^{-} concentration (mg L^{-1})	180-196	185-189	89-102	135-151

[a] YRW was the high-sediment water imported from the Yellow River; SLW was the brackish water brought from the local lake; MXW was their 1:1 mixed water in volume; the results in Table 1 were obtained from seven samples in 2015 and six samples in 2017 of each type of water source applied. "—" in the table indicated it was not tested.

Table 2 Treatments and working conditions included in the experiments[a]

Case	Water source	Flushing	Fertilizer	Operating control	Labels for the operating modes	Duration mode and time	Emitters included in the experiments
1	YRW	No	No	TOTC	YRW+Non_Flus+Fert_0+TOTC	540-660 h (9 h/day)	FE1、FE2、FE6、FE7、FE8、FE9
2	YRW	Yes	No	TOTC	YRW+Flus+Fert_0+TOTC	600-720 h (9 h/day)	FE1、FE2、FE6、FE7、FE8、FE9
3	SLW	Yes	No	TOTC	SLW+Flus+Fert_0+TOTC	660-840 h (9 h/day)	FE1、FE6、FE7、FE8、FE9
4	MXW	Yes	No	TOTC	MXW+Flus+Fert_0+TOTC	540-720 h (9 h/day)	FE1、FE2、FE6、FE7、FE8、FE9
5	YRW	No	No	TEDC	YRW+Non_Flus+Fert_0+TEDC	64 days (15.0 m^3/day)	FE1、FE2、FE3、FE4、FE5、FE6
6	YRW	No	UP 0.15g/L	TEDC	YRW+Non_Flus+Fert_UP0.15+TEDC	64 days (15.0 m^3/day)	FE1、FE2、FE3、FE4、FE5、FE6
7	YRW	No	UP 0.30g/L	TEDC	YRW+Non_Flus+Fert_UP0.30+TEDC	64 days (15.0 m^3/day)	FE1、FE2、FE3、FE4、FE5、FE6
8	YRW	No	PPM 0.15g/L	TEDC	YRW+Non_Flus+Fert_PPM0.15+TEDC	64 days (15.0 m^3/day)	FE1、FE2、FE3、FE4、FE5、FE6
9	YRW	No	PPM 0.30g/L	TEDC	YRW+Non_Flus+Fert_PPM0.30+TEDC	64 days (15.0 m^3/day)	FE1、FE2、FE3、FE4、FE5、FE6
10	YRW	No	APP 0.15g/L	TEDC	YRW+Non_Flus+Fert_APP0.15+TEDC	64 days (15.0 m^3/day)	FE1、FE2、FE3、FE4、FE5、FE6
11	YRW	No	APP 0.30g/L	TEDC	YRW+Non_Flus+Fert_APP0.30+TEDC	64 days (15.0 m^3/day)	FE1、FE2、FE3、FE4、FE5、FE6
12	YRW	No	PPM 0.15g/L	TEDC	YRW+Non_Flus+P1/1+Fert_PPM0.15+TEDC	112 days (7.5 m^3 each time)	FE1、FE3、FE5
13	YRW	No	PPM 0.15g/L	TEDC	YRW+Non_Flus+P1/4+Fert_PPM0.15+TEDC	112 days (30.0 m^3 each time)	FE1、FE3、FE5
14	YRW	No	PPM 0.15g/L	TEDC	YRW+Non_Flus+P1/7+Fert_PPM0.15+TEDC	112 days (52.5 m^3 each time)	FE1、FE3、FE5

[a] YRW was the high-sediment water imported from the Yellow River; SLW was the brackish water brought from the local lake; MXW was their 1:1 mixed water in volume; UP, PPM and APP were the urea phosphate, ammonium polyphosphate and potassium phosphate monobasic, respectively; 0.15 g/L and 0.30 g/L were the two concentrations of fertilizers applied; TOTC and TEDC indicated the system operated based on the total operation time control and the total emitter discharge control, respectively; P1/1, P1/4 and P1/7 showed the irrigation frequencies of the system were once every day, four days and seven days, respectively; Flus and Non_Flus represented with and without flushing treatment; Fert_0 indicated the system operated without fertilization; emitters included in the experiments (FE1-FE9) were the flat emitters summarized in Table 3.

Table 3 Manufacturing and geometric parameters emitters used in the experiments[a]

Emitter	Initial outflow Q ($L\cdot h^{-1}$)	Geometric parameters (mm)			Manufacturing variation coefficient	Manufacturing place
		Length L	Depth D	Width W		
FE1	1.60	35.87	0.72	0.66	0.032	Israel
FE2	1.75	50.00	0.74	0.73	0.035	China
FE3	0.95	61.24	0.55	0.51	0.030	Israel
FE4	1.40	27.34	0.56	0.41	0.038	China
FE5	1.90	30.22	0.55	0.63	0.036	Israel
FE6	2.00	37.98	0.84	0.72	0.034	China
FE7	1.38	39.76	0.69	0.63	0.037	China
FE8	1.40	25.00	0.52	0.63	0.041	China
FE9	2.80	41.10	0.56	0.72	0.034	China

[a] The initial outflows and geometric parameters of the emitters were tested before the experiment; the manufacturing variation coefficients were obtained from the manufacturers.

Table 4 Consistency of anti-clogging ability with different reference emitters for CRI_Dra calculation[a]

Emitter	Reference emitter: FE1		Reference emitter: FE3		Reference emitter: FE6		Reference emitter: FE9	
	CRI_Dra	Ranking	CRI_Dra	Ranking	CRI_Dra	Ranking	CRI_Dra	Ranking
FE1	1.00	5	0.81	4	0.94	7	1.10	4
FE2	0.99	6	0.83	4	0.95	5	1.12	3
FE3	1.14	2	1.00	1	1.06	2	——	
FE4	1.06	3	0.85	2	1.02	3	——	
FE5	0.95	7	0.77	6	0.95	5	——	
FE6	1.01	4	0.83	3	1.00	4	1.14	2
FE7	1.20	1	——		1.11	1	1.34	1
FE8	0.89	8	——		0.87	8	1.03	5
FE9	0.80	9	——		0.84	9	1.00	6

[a] The line "—" in Table 4 indicated no shared working condition with the reference emitter and thus no CRI_Dra value was obtained under this condition.