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Research Article

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Posted Date: January 3rd, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2399573/v1

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Additional Declarations: No competing interests reported.
Risk assessment method for emitter clogging in drip irrigation systems

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Abstract: Risk assessment of drip irrigation system emitter clogging is critical for the system's safe operation. In this paper, the emitter clogging risk and the calculation method are proposed based on risk theory and fuzzy comprehensive evaluation method to quantify the emitter clogging risk during drip irrigation system operation. Moreover, dynamic Bayesian network and emitter clogging degree monitoring data are combined to evaluate the drip irrigation system's emitter clogging risk. The relationship between drip flow channel structure, drip irrigation water quality, drip irrigation system operation, management mode, drip irrigation environment, and the emitter clogging risk of drip irrigation system is established. Based on the established relationship, the influence probability of different influencing factors on emitter clogging is obtained by expert experience and the Fuzzy membership function. Lastly, an emitter-clogging risk level table of the drip irrigation system is constructed. The results show that the model can better reflect the emitter clogging risk of the drip irrigation system and replace the occurrence probability of emitter clogging with fuzzy probability. In addition, the proposed model can quantitatively evaluate the probability of emitter clogging while risk factors can be identified, prevented, and controlled quickly and accurately. The sensitivity analysis shows that employing a fuzzy comprehensive evaluation method to calculate the probability of emitter clogging is reasonable and feasible. A risk level table can be employed to clarify the clogging risk status of the drip irrigation system, which can provide decision support and early warning treatment for drip irrigation system operation and management according to different clogging risk levels. Finally, corresponding anti-clogging measures can improve the system's life and operation efficiency.

Keywords: Emitter clogging; Risk assessment; Fuzzy comprehensive evaluation; Fuzzy probability; Dynamic Bayesian Network

1 Introduction

Drip irrigation technology saves water, energy, and fertilizer and suppresses weeds (Baryosef et al. 1991). As one of the core components of the drip irrigation system, the emitter has a complex flow channel structure and a narrow size (only 0.5-1.2 mm). This can easily lead to emitter clogging, degrading the irrigation quality of the drip irrigation system and eventually leading to the scrapping of the entire drip irrigation system (Pei et al. 2014). Therefore, emitter clogging is a bottleneck problem that affects
Numerous factors affect emitter clogging, such as water quality, drip flow channel structure and size, irrigation frequency, operation management practices, and irrigation environment (Bucks et al. 1979, Capra and Scicolone 1998; Wang et al. 2014). Water quality directly affects emitter clogging in drip irrigation systems. Clogging is usually classified into three types: physical, chemical, and biological (Bucks et al. 1979; Liu et al. 2019; Nakayama and Bucks 1991). Ca\(^{2+}\) and Mg\(^{2+}\) ions in water can produce precipitates deposited in the flow channel, which causes emitter clogging, especially when irrigation water pH levels are high (Lili et al. 2016; Oron et al. 1999; Sopper and William 1991; Li et al. 2008).

Sediment particle size and sand content are important factors affecting emitter clogging (Liu and Niu 2012b; Wu et al. 2014). Emitter flow channel structure, the flow pattern, and flow movement mode are different, and the process of emitter clogging is also different (Zhang et al. 2013; Guo et al. 2018). Various working pressures differently affect emitter clogging (Liu et al. 2019). Moreover, the emitter clogging risk may increase when high sand content water is irrigated using low working pressure (Widaa et al. 2017). The operation mode of drip irrigation and fertilization systems significantly affects emitter clogging (Zhou et al. 2019b). Higher water temperature is characterized by improved anti-physical clogging resistance (Niu and Liu 2012). The possibility of emitter clogging varies among different influencing factors and degrees of clogging.

Although researchers have considered the factors affecting emitter clogging and conducted studies on the assessment of emitter clogging risk (Wu and Niu 2014; ZhangZhong 2016; Zhou 2016), it is not possible to quantitatively assess the emitter clogging risk in drip irrigation systems under specific irrigation conditions. Moreover, a quantitative relationship between influencing factors and clogging risk is still not established. Therefore, a method that objectively and quantitatively assesses emitter clogging risk in drip irrigation systems should be established to quantify emitter clogging risk during drip irrigation system operation. In addition, the qualitative and quantitative analysis should determine the quantitative relationship between different influencing factors and drip irrigation system clogging risk. Emitter clogging risk assessment can be employed to confirm clogging severity and possibility, support decision support for managers, and utilize effective measures to prevent and control drip irrigation system clogging risks.

This emitter clogging risk assessment method is proposed in this paper based on the fuzzy comprehensive evaluation method and dynamic Bayesian network method. Furthermore, a drip irrigation system clogging risk assessment model is established to quantitatively assess the change of emitter clogging risk with irrigation time during drip irrigation system operation. Lastly, guidance suggestions are provided for drip irrigation system configuration and operation management.

2 Establishment of risk assessment methods

The drip irrigation system comprises a water source, pressurizing equipment, filtering device, fertilizer (drug) device, measuring and control device, water transmission, distribution pipeline, and emitter. However, emitter clogging may occur during drip irrigation system operation. Emitter clogging refers to the phenomenon that inorganic, organic, microbial, or chemical precipitation substances in the irrigation quality, service life of the drip irrigation system, and large-scale promotion and application of drip irrigation technology (Nan et al. 2019; Yu et al. 2014).
irrigation water are attached and deposited in the pipe network or drip flow channel of the drip irrigation system. This reduces the emitter cross-section or completely blocks it, decreasing the drip flow and irrigation uniformity (Liu and Niu 2012a). During actual irrigation, emitters easily clog under the combined influence of their structural parameters, irrigation water characteristics, drip irrigation system operation, management mode, and drip irrigation environment (Muhammad et al. 2021; Pei et al. 2014; Zhang et al. 2020; Zhou et al. 2017). Emitter clogging has certain randomness and contingency. The possibility and severity of emitter clogging caused by different influencing factors vary greatly, i.e., the emitter clogging risk caused by different influencing factors varies. Quantifying the probability of emitter clogging and the clogging degree of the drip irrigation system is required to quantitatively assess the emitter clogging risk during drip irrigation system operation.

Risk usually refers to the combination of the possibility of specific hazardous events or accidents and the severity of the consequences. Therefore, emitter clogging risk in drip irrigation systems can be defined as the product of the probability of emitter clogging caused by various factors (such as emitter channel structure, irrigation water quality, operation management mode of a drip irrigation system, and drip irrigation environment during the operation of drip irrigation system), and the degree of clogging caused by emitter clogging. The emitter clogging risk of drip irrigation systems can be calculated as follows:

\[ R = P \times C \]  

where \( R \) is the emitter clogging risk of the drip irrigation system; \( P \) is the emitter clogging probability; \( C \) is the emitter clogging degree.

### 2.1 Emitter clogging probability calculation

Different influencing factors vary emitter clogging probability of drip irrigation systems. Hence, it is difficult to obtain detailed statistical data on the probability of causing emitter clogging (Cheng et al. 2019). Fuzzy comprehensive evaluation method (Kaya et al. 2019; Yao et al. 2019) is an evaluation method based on fuzzy mathematics. The method transforms qualitative into quantitative evaluation using fuzzy linear transformation and affiliation function. Moreover, this method can combine multiple methods for fuzzy calculation of multiple sub-objectives in problems that are difficult to quantify. The membership function divides the evaluation indexes into grades to evaluate their fuzzy relationship and conduct inductive evaluation (Adamo 1980). Therefore, the fuzzy comprehensive evaluation method calculates the influence probability of different factors on emitter clogging occurrence. The specific method is defined in the following subsections.

### 2.1.1 Acquisition of impact factor assessment language

Influence probabilities of different influencing factors on emitter clogging are obtained via expert knowledge and fuzzy logic. Expert knowledge helps to assess the probability of influencing factors in the process. Different field experts must determine the probability of emitter clogging caused by different influencing factors based on their knowledge and experience. Due to the incompleteness, imprecision, and ambiguity of information, experts cannot directly provide the exact probability values of different influencing factors. It is practical for experts to express their opinion about the probability of emitter clogging through assessment language. Fuzzy logic can deal with the probability of failure uncertainty expressed as a language evaluation (Zadeh 1999). Different influencing factors of emitter clogging
probability were described in seven classes (assessment language): “very high” (VH), “high” (H), “relative high” (RH), “medium” (M), “relative low” (RL), “low” (L), and “very low” (VL).

2.1.2 Conversion of evaluation language into fuzzy numbers

Natural language is transformed into mathematical language through fuzzy membership functions (Cheng et al. 2019). Fuzzy membership functions are typically used to represent the possibility of event failure. The most common membership functions representing fuzzy probability are trapezoidal and triangular fuzzy membership functions (Sun et al. 2016). Therefore, the triangular and trapezoidal fuzzy membership functions were combined to calculate the mapping relationship between evaluation language and fuzzy function (Yang et al. 2018; Chen et al. 1992; Zou et al. 2017). The fuzzy membership functions corresponding to the seven evaluation languages are shown in Fig. 1, and the specific calculation is shown in Eqs. (2)-(8).

![Fuzzy membership function](image)

**Fig. 1 Fuzzy membership function**

\[ f_v(x) = \begin{cases} 
1 & 0 < x \leq 0.1 \\
\frac{0.2 - x}{0.1} & 0.1 \leq x \leq 0.2 \\
0 & \text{otherwise} 
\end{cases} \]  \hspace{1cm} (2)

\[ f_h(x) = \begin{cases} 
\frac{x - 0.1}{0.1} & 0.1 \leq x \leq 0.2 \\
\frac{0.3 - x}{0.1} & 0.2 \leq x \leq 0.3 \\
0 & \text{otherwise} 
\end{cases} \]  \hspace{1cm} (3)

\[ f_m(x) = \begin{cases} 
\frac{x - 0.2}{0.1} & 0.2 < x \leq 0.3 \\
1 & 0.3 < x \leq 0.4 \\
\frac{0.5 - x}{0.1} & 0.4 < x \leq 0.5 \\
0 & \text{otherwise} 
\end{cases} \]  \hspace{1cm} (4)

\[ f_r(x) = \begin{cases} 
\frac{x - 0.4}{0.1} & 0.4 < x \leq 0.5 \\
\frac{0.6 - x}{0.1} & 0.5 < x \leq 0.6 \\
0 & \text{otherwise} 
\end{cases} \]  \hspace{1cm} (5)
The evaluation language of different influencing factors is obtained by inviting experts in related fields. Considering the differences in their work relevance, experience, and knowledge of different experts, they may give different evaluation language for the same influencing factor, regardless of their rich professional knowledge and experience. Hence, the Analysis Hierarchy Process (AHP) (Shi et al. 2014) is employed for weighting to balance the differences and ensure the accuracy of evaluation results. The weighted result can be expressed as follows:

\[
 u_{z}(x) = \sum_{c=1}^{n} \omega_j \times u_{c,j}, c = 1, 2, \ldots, d; j = 1, 2, \ldots, g
\]  

where \( u_{z}(x) \) is the weighted membership function; \( \omega_j \) is the weight of an expert \( j \); \( u_{c,j} \) is the membership function corresponding to the evaluation language provided by the \( j \)th expert for the \( c \) influencing factor.

### 2.1.3 Expert weight determination based on AHP

AHP is a systematic method proposed by Satty that integrates quantitative and qualitative analysis to quantify the importance of multiple factors and enable a more rational and scientific systematic decision analysis of multi-objective problems (Saaty and Kearns 1985). The relative importance (weight) of each expert is determined by constructing an evaluation matrix. The weights are also tested for consistency to determine whether the results are reasonable; if not, the evaluation matrix should be adjusted until the results are satisfactory. The specific calculation method is as follows:

1. **Constructing the evaluation matrix**

   The elements in the evaluation matrix represent the relative importance of indicators at the same level. By comparing indicators of each level in pairs, the relative importance of two indicators according to the saaty1-9 scale method (Saaty 2000) is used for the scale assignment, as shown in Table 1. The evaluation matrix \( A \) is constructed according to Eq. (21):

   \[
   A = \begin{bmatrix}
   a_{11} & a_{12} & \cdots & a_{1n} \\
   a_{21} & a_{22} & \cdots & a_{2n} \\
   \vdots & \vdots & \ddots & \vdots \\
   a_{n1} & a_{n2} & \cdots & a_{nn}
   \end{bmatrix}
   \]

   where \( a_{ij} \) is the relative importance of indicator \( i \) compared to indicator \( j \).

   

### Table 1

<table>
<thead>
<tr>
<th>Importance value scale</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Two factors have equal importance</td>
</tr>
<tr>
<td>3</td>
<td>First factor is slightly more important than the second factor</td>
</tr>
</tbody>
</table>
where $b_{ij}$ denotes the comparison result of the $s$th element relative to the $d$th element; if $s = d$, then $b_{sd} = 1$, the where $b_{sd} = 1/ b_{ds}$.

(2) Consistency testing

The consistency ratio (CR) is considered necessary for directly measuring the consistency between two comparisons. The maximum eigenvalue of the evaluation matrix is obtained, and the CR value is calculated according to Eqs. (22) and (23). If $CR < 0.1$, the evaluation matrix is considered to pass the consistency test:

$$CI = \frac{\lambda_{\text{max}} - m}{m - 1}$$  \hspace{1cm} (11)

$$CR = \frac{CI}{RI}$$  \hspace{1cm} (12)

where $\lambda_{\text{max}}$ is the maximum eigenvalue of the evaluation rectangle; $m$ is the order of the evaluation matrix; CI is the consistency index; RI is the random consistency index, whose values are shown in Table 2.

**Table 2** The random consistency index (RI) (Vaidya 2006)

<table>
<thead>
<tr>
<th>$n$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR</td>
<td>0.00</td>
<td>0.00</td>
<td>0.58</td>
<td>0.90</td>
<td>1.12</td>
<td>1.24</td>
<td>1.32</td>
<td>1.41</td>
<td>1.45</td>
<td>1.49</td>
</tr>
</tbody>
</table>

(3) Solving for the weights

Elements of each column of the evaluation matrix are normalized:

$$K_s = \frac{b_{s*}}{\sum_{j=1}^{m} b_{s*}} \text{ (} s=1,\ldots,g \text{)}$$  \hspace{1cm} (13)

The normalized evaluation matrix is summed in rows:

$$K_m = \sum_{s=1}^{g} K_{s*}$$  \hspace{1cm} (14)

Vector $K_m$ is normalized, obtaining the resulting feature vector $\omega_m$ as the weight:

$$\omega_m = \frac{K_m}{\sum_{m=1}^{g} K_m}$$  \hspace{1cm} (15)

Personal experience, knowledge, information sources, and evaluation impartiality of different experts can lead to significant differences in evaluation results. Therefore, the relative importance of different experts is ranked according to the evaluation matrix to reduce differences in the subjective evaluation of different experts. Firstly, the priority relationship matrix of four elements representing experts' ability, such as personal experience, knowledge, information sources, and fairness of evaluation,
is constructed. Levels of different experts are further compared by employing any of the four elements (such as personal experience) as a criterion. The remaining three elements are metrics used to construct a comparison matrix for all experts.

Expert weight is determined by four factors: personal experience, knowledge, information sources, and evaluation impartiality. Comprehensive weights for each expert are calculated by Eq. (16):

$$V_j = W_{FE,E} \times W_{E,j} + W_{KE,E} \times W_{K,j} + W_{SE,E} \times W_{S,j} + W_{IE,E} \times W_{I,j}$$ (16)

where $V_j$ is the combined weight of an expert $j$; $W_{FE,E}$ is the weight of personal experience ($E$) in four elements (FE); $W_{E,j}$ is the single weight of expert $j$ under personal experience; $K$ represents knowledge, $S$ represents information source, and $I$ represents the fairness of the evaluation.

2.1.3 Converting fuzzy numbers into clogging probabilities

Fuzzy number to clogging probability conversion is divided into two parts: fuzzy number to fuzzy probability conversion, and fuzzy probability to clogging probability conversion. Fuzzy probability contains two aspects of fuzziness and probability that directly show the complexity of quantifying inescapable problems more authoritatively (Cheng et al. 2019). Moreover, the fuzzy probability is a membership function that defines fuzzy numbers in the probability space and is used to quantitatively express the probability characteristics of events. The emitter clogging has certain characteristics of randomness, fuzziness, and complexity. The risk of emitter clogging is quantitatively evaluated according to the model established by the concept of fuzzy mathematics, which is consistent with the characteristics of emitter clogging. In this paper, the maximum and minimum setting methods are used to obtain fuzzy probability (Chen et al. 1992). First, the maximum and minimum fuzzy sets are defined as follows:

$$u_{\text{max}} = \begin{cases} x & 0 \leq x \leq 1 \\ 0 & \text{otherwise} \end{cases} \quad (17)$$

$$u_{\text{min}} = \begin{cases} 1 - x & 0 \leq x \leq 1 \\ 0 & \text{otherwise} \end{cases} \quad (18)$$

Then, the left and right effective scores are obtained according to the method shown in Fig. 2.

![Fig. 2 Maximum and minimum setting method](image)

$P_R$ and $P_L$ are left and right effective scores, respectively; $u_d(x)$ is the membership function after weighting; $u_{\text{max}}(x)$ and $u_{\text{min}}(x)$ are the maximum and minimum fuzzy sets, respectively.
\[ P_R = \sup \left[ u_Z(x) \cap u_{\text{max}}(x) \right] \]
\[ P_L = \sup \left[ u_Z(x) \cap u_{\text{min}}(x) \right] \]

where \( P_R(Z) \) is the right effective score and \( P_L(Z) \) is the left significant score.

The fuzzy probability (Chen 1985) can be written as follows:
\[ P_u = \frac{(P_u + 1 - P_u)}{2} \]

Onisawa (Hu et al. 2019; Takehisa. 1990) equation is used to transform the clogging probability.
\[ P = \begin{cases} 10^{-k} & P_u \neq 0 \\ 0 & P_u = 0 \end{cases} \]
\[ k = \left[ \frac{1 - P_u}{P_u} \right]^{0.5} \times 2.301 \]

### 2.1.4 Influence of time factor on the clogging risk

The actual irrigation needs to consider the influence of the time factor on emitter clogging. When the drip irrigation system operates, impurities such as suspended particles, soluble chemicals, microorganisms, and organic matter in the irrigation water tend to collect and deposit inside the drip flow channel due to the complex structure and narrow size of the drip flow channel. Consequently, the overflow section of a drip flow channel gradually changes (Liu et al. 2015), and the emitter clogging gradually occurs with an increase in irrigation time. Moreover, emitter clogging will become increasingly serious. Emitter clogging probability also increases gradually with irrigation time. Therefore, Dynamic Bayesian Network (DBN) is used to calculate the effect of irrigation time on emitter clogging during the operation of drip irrigation systems. In other words, the DBN transfer probability is the probability that the irrigation time will affect the occurrence of emitter clogging.

DBN (Wu et al. 2016) is an extension of Bayesian networks in time series, specifically in the presence of directed arcs spanning time slices. DBN decomposes the initial and transition networks under the steady-state Markov assumption (Wang et al. 2017). The initial probability distribution is:
\[ P(X) = \prod_{i=1}^{N} P(r_i, Pa(r_i)) \]

The probability distribution of adjacent transfer is:
\[ P(X_t | X_{t-1}) = \prod_{i=1}^{N} P(r'_i | Pa(r'_i)) \]

where \( X = \{ r_1, r_2, \ldots, r_N \} \) is the set of all nodes in BN; \( Pa(x_i) \) is the parent node of \( r_i \) node; \( r'_i \) is the \( i \)th node on the \( t \)th time segment; \( Pa(r'_i) \) is the \( r'_i \) parent node.

Assuming that the emitter clogging occurrence probability follows an exponential distribution, the transfer probability is calculated according to the influence probability (\( \lambda \)) of the drip flow channel structure and irrigation water quality on emitter occurrence clogging. Then, the adjacent irrigation time interval (\( \Delta t \)) is the transfer probability \( P(t) \) from the current moment (\( t \)) to the next moment (\( t + \Delta t \)), i.e.:
\[ P(t) = P(r'_i (t + \Delta t) | r_i(t)) = \int_{t}^{t+\Delta t} \lambda \exp(-\lambda t) dt = 1 - \exp(-\lambda \Delta t) \]

### 2.2 Calculation of the clogging degree

The discharge ratio variation (Dra) can characterize the overall clogging level of the entire drip
irrigation system. The amount of emitter Dra variation is used to evaluate the emitter clogging degree ($C$) of the drip irrigation system. Dra variation can be calculated according to (Liu et al. 2019) as follows:

$$Dra = \frac{\sum q_i}{e \times q_0} \times 100\%$$  \hspace{1cm} (26)

$$C = 5 + \log(100 - Dra)$$  \hspace{1cm} (27)

where Dra is the relative flow rate of emitters, $\%$; $q_i$ is the test flow rate of emitters, L/h; $q_0$ is the initial flow rate of emitters, L/h; $e$ is the number of emitters; $C$ indicates the emitter clogging degree.

3 Risk assessment model for drip irrigation system emitter clogging

The risk assessment model of drip irrigation system emitter clogging is constructed according to the clogging risk assessment method introduced in Section 1. The specific introduction of risk assessment for drip irrigation system emitter clogging is shown in Fig. 3.

3.1 Selection the influencing factors of emitter clogging in drip irrigation system

Emitter clogging in drip irrigation systems is influenced by water quality (such as particle size, content, surface characteristics of suspended particulate matter in irrigation water, pH, Ca$^{2+}$, Mg$^{2+}$ ion content, microbial content and type, organic matter content) (Bounoua et al. 2016; Liu et al. 2019; Liu et al. 2018; Zhangzhong et al. 2021), drip flow channel structure (such as flow channel length, depth, width, tooth height, tooth angle, tooth spacing, emitter type) (Liu and Huang 2009), drip irrigation system operation and management mode (such as filtration equipment, irrigation frequency, working pressure, irrigation time) (Li et al. 2015; Yu et al. 2018; Liu et al. 2019; Zhou et al. 2019b) and drip irrigation environment (e.g., irrigation water temperature and air temperature) (Liu et al. 2016). Specific influencing factors of emitter clogging should be determined based on the actual irrigation situation and data acquisition of influencing factors.

3.2 Calculation of clogging probability and degree of drip irrigation system

The methods introduced in Sections 2.1 and 2.2 are used to calculate the emitter clogging probability and clogging degree of the drip irrigation system. Different experts engaged in the work related to wa-
saving irrigation technology were invited to obtain the evaluation languages of different experts on the influencing factors using an anonymous questionnaire. These factors are based on the test data of various influencing factors. Then, the mapping relationship between the evaluation language and the fuzzy function was calculated by combining fuzzy membership functions (Fig. 1). Next, the evaluation language was transformed into fuzzy numbers using Eqs. (2)-(8). Comprehensive consideration is given to the impact of the experts' personal experience, knowledge, information sources, and impartiality of the evaluation to balance differences between evaluation languages from different experts. AHP is used for the weighting process to calculate the weights of different experts according to the weighted membership function:

\[
u_c(x)= \begin{cases} 
\frac{x-a}{b-a} & a \leq x < b \\
1 & b \leq x \leq c \\
\frac{c-x}{d-c} & c < x \leq d \\
0 & \text{otherwise}
\end{cases}
\]  

The fuzzy numbers are translated into fuzzy probabilities using the maximum and minimum setting methods. The Onisawa formula is used for fuzzy probability transformation to obtain the influence probability of different influencing factors on emitter clogging. DBN calculates the influence probability of irrigation time on emitter clogging in a drip irrigation system. The adjacent irrigation time interval ($\Delta t$) is defined as the duration of each irrigation in the drip irrigation system during the emitter clogging risk assessment. The influence probability of irrigation time on emitter clogging of drip irrigation system is calculated via Eq. (16) - Eq. (18). The change in the channel structure of an irrigation time drip flow $X_I$ and drip irrigation water quality $X_J$ affect the probability $\lambda$ of emitter clogging the drip irrigation system as follows:

\[
\lambda = P(X_I)P(X_J)
\]  

where $P(X_I)$ and $P(X_J)$ are the influence probability of $X_I$ and $X_J$ on emitter clogging, respectively.

Finally, the probability of emitter clogging of drip irrigation system is calculated by accumulating the influence probability of different factors on emitter clogging (Eq. 30). The emitter blockage probability of the drip irrigation system is shown in Eq. (31). The clogging degree of a drip irrigation system is calculated according to Eq. (27)

\[
P(T) = \sum_{i=1}^{c} P_i
\]

where $P(T)$ is the emitter clogging probability; $P_i$ is the influence factor $x_i$ on the drip head emitter clogging probability; $P(t)$ is the transfer probability; $i$ is the number of emitter flow tests (i.e., the number of irrigations).

### 3.3 Classification of emitter clogging risk for a drip irrigation system

The emitter clogging risk value of the drip irrigation system is calculated according to Eq. (1). The emitter clogging risk of the drip irrigation system is divided into five levels according to the definition of clogging risk, as shown in Fig. 4. According to the risk definition, the risk assessment rating table is a combination of the severity and probability of the consequences of a specific event. Making risk assessment rating tables is a common risk analysis method important for clarifying the impact of
randomness and inevitability of emitter clogging on the drip irrigation system operation. According to Wu et al. (2008) and other criteria for the emitter clogging degree classification, the emitter clogging degree is divided into five classes, and the specific classification criteria are shown in Table 3. The clogging probability class (Chung 2021) is classified according to Table 4.

![Table 3 Classification of emitter clogging degree](image)

Fig. 4 Risk assessment grade of drip irrigation system emitter clogging

### Table 3 Classification of emitter clogging degree

<table>
<thead>
<tr>
<th>Description</th>
<th>Dra value range</th>
<th>C value range</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unclogged</td>
<td>[100,95)</td>
<td>[0,5.70)</td>
<td>1</td>
</tr>
<tr>
<td>Slight clogging</td>
<td>[95,80)</td>
<td>[5.70,6.30)</td>
<td>2</td>
</tr>
<tr>
<td>General Clogging</td>
<td>[80,50)</td>
<td>[6.30,6.90)</td>
<td>3</td>
</tr>
<tr>
<td>Severe clogging</td>
<td>[50,20)</td>
<td>[6.90,6.98)</td>
<td>4</td>
</tr>
<tr>
<td>Completely clogged</td>
<td>[20,0)</td>
<td>[6.98,7.00)</td>
<td>5</td>
</tr>
</tbody>
</table>

![Table 4 Classification of emitter clogging probability](image)

### Table 4 Classification of emitter clogging probability

<table>
<thead>
<tr>
<th>Qualitative description</th>
<th>Congestion probability</th>
<th>Evaluation Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low risk</td>
<td>&lt;0.0003</td>
<td>1</td>
</tr>
<tr>
<td>Low risk</td>
<td>0.0003–0.003</td>
<td>2</td>
</tr>
<tr>
<td>Medium risk</td>
<td>0.003–0.03</td>
<td>3</td>
</tr>
<tr>
<td>High risk</td>
<td>0.03–0.3</td>
<td>4</td>
</tr>
<tr>
<td>Very high risk</td>
<td>0.3–1.0</td>
<td>5</td>
</tr>
</tbody>
</table>

3.4 Sensitivity and importance analysis

Emitter clogging risk assessment of drip irrigation systems is a simple and effective method for determining the influence probability of different factors on emitter clogging with the help of expert experience. However, the influence of human subjective factors is inevitable; hence, the accuracy of model application and reliability of evaluation results cannot be guaranteed. Sensitivity analysis can identify the main factors affecting the evaluation of emitter clogging risk, which is an essential step in multi-criteria decision-making. Sensitivity analysis is directly related to the accuracy and reliability of evaluation results. Moreover, it gives decision-makers additional control over drip irrigation systems’ operation and management. In addition, sensitivity analysis provides a theoretical basis for promoting the operation and management of drip irrigation systems and high-quality operation. Sensitivity analysis is performed according to Eq. (32) (Hu et al. 2019):
$$I_S = \frac{1 - \prod (1 - P_c)}{P(T)}$$  \hspace{1cm} (32)$$

where $I_S$ is the sensitivity coefficient; $P_c$ is the influence factor $x_c$ on the emitter clogging probability (CP); $P(T)$ is the emitter clogging probability.

4 Application of the risk assessment model

The experimental data results of Liu et al. (2019) were used to analyze the emitter clogging risk of drip irrigation systems and verify the efficiency and feasibility of the emitter clogging risk assessment model for drip irrigation systems. The experiment was conducted at Ulan Buhe Irrigation Station (40°24'32" N, 107°02'19" E) in the north of Dengkou County, Bayannaoer City, Inner Mongolia Autonomous Region, China. The station is west of the Hetao irrigation area, with an altitude of 1072 meters. According to the experimental results of Zhou et al. (2019a), the area belongs to the arid/semi-arid and semi-desert steppe zone. The climate is characterized as the temperate plateau, which belongs to the temperate plateau or continental climate with an average temperature of 26.3°C-38.7°C. The experimental layout and test materials of the drip irrigation system are detailed in Liu et al. (2019). The filtration system includes a sand sink, sand filter (filter material particle size of 0.9 mm - 1.3 mm), and a stacked filter (mesh: 150). The test data with a working pressure of 60 kPa were selected for model validation. The total test time was 720 h, the irrigation time was eight hours every day, and the emitter flow rate was tested every 60 h. Four types of non-pressure compensated emitter irrigation belts with an inner diameter of 16 mm were selected for the test. The structural parameters of four emitters are shown in Table 5.

<table>
<thead>
<tr>
<th>Label</th>
<th>Initial outflow $Q_{(L/h)}$</th>
<th>Flow path width $W$ (mm)</th>
<th>Flow path depth $D$ (mm)</th>
<th>Flow path length $L$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE1</td>
<td>0.8</td>
<td>0.45</td>
<td>0.50</td>
<td>21.5</td>
</tr>
<tr>
<td>FE2</td>
<td>1.0</td>
<td>0.50</td>
<td>0.50</td>
<td>23.0</td>
</tr>
<tr>
<td>FE3</td>
<td>1.2</td>
<td>0.52</td>
<td>0.63</td>
<td>23.0</td>
</tr>
<tr>
<td>FE4</td>
<td>1.6</td>
<td>0.52</td>
<td>0.63</td>
<td>29.7</td>
</tr>
</tbody>
</table>

4.1 Selection of influencing factors for emitter clogging

According to national and industrial standards, specifications, and technical requirements (Bucks et al. 1979), research results of domestic experts (Hou et al. 2020; Li et al. 2018; Liu et al. 2018; Wen et al. 2020) and combined with the actual irrigation conditions of drip irrigation system, the main influencing factors of emitter clogging can be classified as 18 influencing factors under four types of elements of emitter flow channel structure, drip water quality, drip irrigation system operation, management mode, and drip irrigation environment. Specific influencing indexes are shown in Fig. 5.
4.2 Emitter clogging probability

In this paper, five experts engaged in research on emitter clogging were invited to obtain the evaluation language of different influencing factors. The relative importance of five experts was ranked using five evaluation matrices. Firstly, the priority relationship matrix of four elements representing the expert’s ability, personal experience, knowledge, source of information, and fairness of evaluation was constructed, as shown in Eq. (33). The levels of different experts were further compared using one of the four elements, such as personal experience (Eq. 34). The remaining three elements were considered as metrics to construct a comparison matrix for all experts, as shown in Eqs. (35)-(37).

\[
A_1 = \begin{bmatrix}
1 & 2 & 2 & 3 \\
\frac{1}{2} & 1 & 3 & 3 \\
\frac{1}{2} & \frac{1}{3} & 1 & 2 \\
\frac{1}{3} & \frac{1}{3} & \frac{1}{2} & 1 \\
\end{bmatrix}
\]  \quad \text{(33)}

\[
A_2 = \begin{bmatrix}
1 & 2 & 3 & 2 & 1 \\
\frac{1}{2} & 1 & 2 & 1 & 2 \\
\frac{1}{3} & \frac{1}{2} & 1 & 1 & 2 \\
\frac{1}{2} & 1 & 1 & 1 & 1 \\
1 & \frac{1}{2} & \frac{1}{2} & 1 & 1 \\
\end{bmatrix}
\]  \quad \text{(34)}

\[
A_3 = \begin{bmatrix}
1 & 3 & 1 & 6 & 1 \\
\frac{1}{3} & 1 & \frac{1}{2} & \frac{3}{2} & \frac{1}{2} \\
1 & 2 & 1 & 6 & 1 \\
\frac{1}{6} & \frac{1}{3} & \frac{1}{6} & 1 & \frac{1}{4} \\
1 & 2 & 1 & 4 & 1 \\
\end{bmatrix}
\]  \quad \text{(35)}

\[
A_4 = \begin{bmatrix}
1 & 2 & 1 & 3 & 3 \\
\frac{1}{2} & 1 & 1 & 2 & 2 \\
1 & 1 & 1 & 2 & 2 \\
\frac{1}{3} & \frac{1}{2} & \frac{1}{2} & 1 & \frac{1}{2} \\
\frac{1}{3} & \frac{1}{2} & \frac{1}{2} & 2 & 1 \\
\end{bmatrix}
\]  \quad \text{(36)}
Various indicators and weights of five experts were determined using AHP, and the results were calculated and shown in Tables 6 and 7.

Table 6 Weights of various criteria of representing expert ability

<table>
<thead>
<tr>
<th>Factors</th>
<th>Criteria</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal experience</td>
<td>Working years, age, job performance</td>
<td>0.4079</td>
</tr>
<tr>
<td>Knowledge</td>
<td>Educational qualification, title</td>
<td>0.3192</td>
</tr>
<tr>
<td>Information source</td>
<td>Experience, literature, experimental data</td>
<td>0.1665</td>
</tr>
<tr>
<td>Impartiality of evaluation</td>
<td>Independence of assessment</td>
<td>0.1064</td>
</tr>
</tbody>
</table>

Table 7 Weight factors of experts under different criteria based on AHP

<table>
<thead>
<tr>
<th>Codes</th>
<th>Personal experience</th>
<th>Knowledge</th>
<th>Information source</th>
<th>Impartiality of evaluation</th>
<th>Comprehensive weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expert 1</td>
<td>0.3147</td>
<td>0.2972</td>
<td>0.3253</td>
<td>0.2125</td>
<td>0.3000</td>
</tr>
<tr>
<td>Expert 2</td>
<td>0.2199</td>
<td>0.1264</td>
<td>0.2096</td>
<td>0.3145</td>
<td>0.1984</td>
</tr>
<tr>
<td>Expert 3</td>
<td>0.1537</td>
<td>0.2741</td>
<td>0.2408</td>
<td>0.0882</td>
<td>0.1997</td>
</tr>
<tr>
<td>Expert 4</td>
<td>0.1667</td>
<td>0.0495</td>
<td>0.0967</td>
<td>0.2585</td>
<td>0.1274</td>
</tr>
<tr>
<td>Expert 5</td>
<td>0.1451</td>
<td>0.2527</td>
<td>0.1275</td>
<td>0.1262</td>
<td>0.1745</td>
</tr>
</tbody>
</table>

The influence probability of different influencing factors on emitter clogging was calculated using the method presented in Section 2.1.3, and the results are shown in Table 8. Due to space limitation, the influence factor $x_1$ on the drip tip FE4 clogging was used as an example. The assessment language of five experts regarding the influence factor $x_1$ on emitter FE4 clogging are VL, L, VL, RL, and L. The fuzzy membership function corresponding to the assessment language is calculated using Eqs. (2)-(9):

$$a(x) = \begin{cases} 
\frac{x - 0.0628}{0.1} & 0.0628 \leq x \leq 0.1628 \\
1 & 0.1628 < x \leq 0.1755 \\
\frac{0.1755 - x}{0.1} & 0.1755 < x \leq 0.2755 \\
0 & \text{otherwise}
\end{cases} (38)$$

Then, using Eqs. (12)-(16), the left and right effective score is calculated as $P_R=0.148$ and $P_L=0.250$; the fuzzy probability value is obtained as $P_M=0.4488$; the clogging probability equals $P=0.003433$.

Table 8 Assessment language and clogging probability for different influencing factors

<table>
<thead>
<tr>
<th>No.</th>
<th>Assessment Language</th>
<th>Clogging probability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FE1</td>
<td>FE2</td>
</tr>
<tr>
<td>$x_1$</td>
<td>L,VL,L,RL,L</td>
<td>L,VL,L,RL,L</td>
</tr>
<tr>
<td>$x_2$</td>
<td>H,RH,MM,H</td>
<td>RH,RH,VH,H</td>
</tr>
<tr>
<td>$x_3$</td>
<td>L,VL,L,VL,VL</td>
<td>L,VL,L,VL,VL</td>
</tr>
<tr>
<td>$x_4$</td>
<td>M,RH,H,M,RH</td>
<td>M,RH,H,H,RH</td>
</tr>
<tr>
<td>$x_5$</td>
<td>RH,H,H,H,RH</td>
<td>HH,H,H,H,RH</td>
</tr>
</tbody>
</table>
The influence probability of emitter clogging was calculated by accumulating the influence probabilities of different influencing factors of drip flow channel structure $X_1$, the management mode of a drip irrigation system operation $X_2$, drip water quality $X_3$, and drip irrigation environment $X_4$. The calculation results are shown in Table 9.

### Table 9 Emitter clogging probability

<table>
<thead>
<tr>
<th>Label</th>
<th>Flow channel structure $X_1$</th>
<th>Operation management mode $X_2$</th>
<th>Drip irrigation water quality $X_3$</th>
<th>Drip irrigation environment $X_4$</th>
<th>Clogging probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE1</td>
<td>0.019007</td>
<td>0.008979</td>
<td>0.025237</td>
<td>0.003012</td>
<td>0.056235</td>
</tr>
<tr>
<td>FE2</td>
<td>0.019439</td>
<td>0.009226</td>
<td>0.025961</td>
<td>0.003348</td>
<td>0.057974</td>
</tr>
<tr>
<td>FE3</td>
<td>0.018973</td>
<td>0.009060</td>
<td>0.02578</td>
<td>0.003377</td>
<td>0.057207</td>
</tr>
<tr>
<td>FE4</td>
<td>0.020407</td>
<td>0.008898</td>
<td>0.02547</td>
<td>0.003588</td>
<td>0.058363</td>
</tr>
</tbody>
</table>

#### 4.3 Influence of irrigation time on emitter clogging

The influence probability of irrigation time on emitter clogging of drip irrigation system is calculated using Eqs. (23)-(25). The influence probability $\lambda$ of emitter clogging by changing drip flow channel structure $X_1$ and drip water quality $X_3$ with irrigation time can be expressed as:

$$\lambda = P(X_1)P(X_3)$$  \hspace{1cm} (39)

where $P(X_1)$ and $P(X_3)$ are influence probabilities of $X_1$ and $X_3$ on emitter clogging, respectively.

In this paper, the adjacent irrigation time interval ($\Delta t$) is set as the time between each emitter flow monitoring as $\Delta t = 60$. The corresponding influence probabilities $\lambda$ of FE1, FE2, FE3, and FE4 emitters are $0.000480$, $0.000505$, $0.000520$, and $0.000489$, respectively. Dynamic variation curves of the four emitters clogging probabilities with irrigation time are shown in Fig. 6.
4.4 Clogging degree of an emitter

The emitter clogging risk in drip irrigation systems is generally manifested by abnormal conditions of emitter flow (gradual or sudden decrease in emitter flow). Perception of these abnormal conditions usually relies on emitter flow monitoring. The drip irrigation system emitter clogging risk assessment method assumes that $D_{rel}$ collected for each irrigation of the drip irrigation system is a small risk contribution. The variation curves of different clogging levels of an emitter with irrigation time are shown in Fig. 7.

5 Results and analysis

5.1 Risk analysis of drip irrigation system emitter clogging

Identifying different influencing factors that may cause the emitter clogging risk can help to develop reasonable anti-clogging measures, reduce the emitter clogging, and extend the service life of the drip irrigation system. Different flow structures ($X_1$) are characterized by various influence probabilities of drip head clogging (Table 9). Moreover, the influence probability of operation management mode ($X_2$), irrigation water quality ($X_3$), and irrigation environment ($X_4$) on the occurrence of different emitters clogging varies significantly. The influence probability of $X_1$ and $X_3$ on the occurrence of emitter clogging is greater than that of $X_2$ and $X_4$. The probabilities of FE1, FE2, FE3, and FE4 emitter clogging are 0.056235, 0.057974, 0.058363, and 0.057207, respectively. The clogging degree significantly varies for
different emitters (Fig. 6). Hazard factors can be quickly and accurately identified and prevented by calculating the influence probability of each influencing factor on emitter clogging. Therefore, the drip irrigation system operation process should try to optimize the control of irrigation water quality to reduce emitter clogging. If drip water quality is difficult to change, the operation management mode of the drip irrigation system should be optimally adjusted. Various clogging degrees are caused by and vary greatly between different emitters. Hence, priority should be given to the emitter with a stronger anti-clogging ability to reduce the emitter-clogging risk of the drip irrigation system.

5.2 Risk assessment of emitter clogging in drip irrigation systems considering the time factor

According to the emitter clogging risk definition, calculation method of drip irrigation system, and the influence of irrigation time on the emitter clogging probability, four types of emitters clogging risk are evaluated, and the emitter clogging risk value ($R$) of drip irrigation system is found. The variation curves of the $R$-value with irrigation time for the four emitters are shown in Fig. 7. According to Fig. 8, the $R$-value gradually increases with irrigation times. Moreover, a linear correlation exists between $R$-values and irrigation time. The clogging risks of four emitters in the irrigation process are FE4 > EF2 > EF3 > FE1, which is consistent with the actual clogging state.

The dynamic change of the emitter clogging risk value of the drip irrigation system with the irrigation time can quantitatively reflect the actual clogging status of the emitter of the drip irrigation system. This provides certain decision support for the management measures of the drip irrigation system according to the clogging risk level in the actual irrigation process (Fig. 9). Hence, the staff can be reminded to take appropriate anti-clogging measures.

Next, preliminary arrangements for the early warning of different emitter-clogging risk states in the drip irrigation system are made. The arrangements are based on the emitter clogging risk classification of the drip irrigation system in Fig. 4, the flushing measures to mitigate the emitter clogging risk by Zhang et al. (2019) and the influence of emitter clogging by chlorination treatment by Li et al. (2010),

- Level 1. The drip irrigation system is working well and does not need to be monitored;
- Level 2. The systems should be monitored to avoid escalation of drip clogging risk in the drip irrigation system; appropriate anti-clogging measures should be taken to mitigate the drip clogging risk in the drip irrigation system;
- Level 3. Some control measures (capillary flushing, acid and chlorine treatment, etc.) need to be immediately taken depending on the degree of drip head blockage;
- Level 4. the drip irrigation system is severely clogged and needs to be prepared for drip tape replacement;
- Level 5. Immediate replacement of drip irrigation tape is required.
5.3 Sensitivity analysis

Sensitivity analysis of influencing factors can identify the main factors influencing emitter clogging risk evaluation and determine the reliability of emitter clogging risk evaluation results of drip irrigation systems. Then, the reliability of influencing factors on emitter clogging risk evaluation results can be verified. The sensitivity coefficients of different influencing factors on the emitter FE1 clogging risk are shown in Fig. 10. Parameters $I_{SI}$ and $CP$ are converted to $-\log(I_{SI})$ and $-\log(CP)$, with smaller values indicating the higher occurrence probability (sensitivity). According to the rank of $I_{SI}$ and $CP$ values for different influencing factors (Fig. 8), the influencing factors that contribute most to the emitter clogging risk are $x_2$, $x_3$, $x_5$, $x_{10}$, $x_{16}$, and $x_{18}$. Therefore, when applying the emitter FE1 irrigation, special attention should be paid to the influence of the abovementioned factors on the clogging risk. The sensitivity analysis shows that calculating the influence probability of different influencing factors on emitter clogging using the fuzzy comprehensive evaluation method is reasonable and feasible. This further validates the emitter-clogging risk assessment model for drip irrigation systems.
6 Conclusions, outlook, and future work

In this paper, the emitter clogging risk assessment method based on the fuzzy comprehensive evaluation method and dynamic Bayesian network method was proposed to analyze the emitter clogging risk of the drip irrigation system quantitatively and qualitatively. The main conclusions are as follows:

(1) The proposed emitter clogging risk assessment model is based on the fuzzy comprehensive evaluation method. This method integrates the influence of drip flow channel structure, water quality, drip irrigation system operation, management mode, and drip irrigation environment on emitter clogging. The influence of irrigation time on emitter clogging was calculated via a dynamic Bayesian network, and the dynamic influence probability of emitter clogging was obtained. The causes and consequences of emitter clogging risk for a drip irrigation system can be quantitatively evaluated. Moreover, the model can be extended according to the specific conditions of the drip irrigation system, which provides a theoretical basis for emitter clogging risk assessment of the drip irrigation system.

(2) The fuzzy comprehensive evaluation method was used to obtain the influence probability of emitter clogging caused by different influencing factors. This can reflect the fuzziness of emitter clogging probability caused by different influencing factors. By calculating the magnitude of the influence factors on emitter clogging probability, weak links of the emitter clogging can be detected, and key points of the clogging protection can be quickly determined.

(3) Establishing the risk rating table of emitter clogging in a drip irrigation system can clarify the risk status of drip irrigation system emitter clogging, contribute to partake in corresponding anti-clogging measures, reasonably avoid the risk of emitter clogging in a drip irrigation system, reduce the risk of clogging, and improve the service life of a drip irrigation system. The reliability of the emitter clogging risk assessment was verified via sensitivity analysis. Lastly, the proposed model was also applied for validation purposes.

Some shortcomings of the proposed method should also be mentioned. The probability of different influencing factors on emitter clogging of drip irrigation systems is mainly scored by different experts and obtained by fuzzy mathematical principles. Experts have subjectivity and uncertainty due to various educational backgrounds, working experiences, and risk attitudes.
In future work, quantitative relationships between emitter clogging and influencing factors in drip irrigation systems should be established to obtain accurate emitter clogging probabilities. The drip irrigation system clogging risk assessment model does not consider the influence of filtering devices on clogging risk. The clogging probability level should be divided concerning other projects and optimized according to the actual irrigation and emitter clogging situation of the drip irrigation system. Lastly, more reasonable suggestions and effective anti-clogging measures should be proposed for the early warning arrangement of the clogging risk status according to the actual situation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We are grateful for the financial support from the Major Scientific and Technological Innovation Projects in Shandong Province (2020CXGC010808) and the National Natural Science Foundation of China (51679205 & 52079112).

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Analytic Hierarchy Process.


