Analysis and Evaluation of Wastewater Quality During Tunnel Construction Based on Drilling and Blasting Method

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Abstract. During the construction of tunnel based on drilling and blasting method, a large amount of wastewater will be produced, in which the types and concentrations of main pollutants will change regularly with the continuous circulation of construction process. In this paper, the wastewater of Hengwu tunnel in the drilling, post blasting, slag discharge and initial support stages is sampled and detected, the main pollutant types and change laws of construction wastewater in each stage are analyzed, and the set pair analysis method is used to evaluate the wastewater quality to determine the degree of wastewater pollution in different construction stages. The research shows that after blasting, the concentration of ammonia nitrogen first reaches the peak, and then other pollution concentrations begin to rise. Different construction stages have different effects on wastewater quality. The construction wastewater generated in the initial support stage of Hengwu tunnel is the most polluted, and the construction wastewater in the drilling stage is the least polluted. The research results of this paper can provide reference for the selection of wastewater treatment process in different construction stages of similar projects.

Keywords. Wastewater, tunnel construction, water quality, set pair analysis

1. Introduction

At present, the construction methods of highway tunnel mainly include drilling and blasting method and TBM method. Drilling and blasting method is widely used in practical engineering because of its flexible operation, can adapt to various geological conditions, and can be used to excavate underground caverns of various shapes and sizes. However, a large amount of wastewater will be produced during construction.

If these wastewaters are directly discharged into the surrounding water environment without treatment, it will not only affect the beauty of the surrounding environment, but also seriously change the physical and chemical properties of the surrounding water body, thus affecting the surrounding ecological environment. For example, excessive solid concentrations in water can change the growth of plants, invertebrates and vertebrates.

According to the research data, if the concentration of suspended solids (SS) exceeds 2000mg/L, it will cause the death of old fish, which will directly affect aquatic organisms.
In addition, high solid concentration will reduce the transparency of water and lead to the fluctuation of water turbidity. A large amount of solid matter will be deposited at the bottom of the river, changing the living environment of the original benthos; Nitrogen pollutants in construction wastewater are also the main substances causing water eutrophication.

Therefore, appropriate processes must be selected for the treatment of wastewater generated in the construction process, but the premise is to clarify the main pollutants and causes in each stage of the construction process. These wastewaters mainly come from the water gushing when the tunnel crosses the unfavorable geological unit, the wastewater generated by construction equipment, the water used for dust reduction after blasting, the wastewater generated during shotcrete and grouting and the bedrock fissure water [2]. The existing research shows that the problems existing in the quality of wastewater discharged during the construction of highway tunnel include suspended solids (SS), potential of hydrogen(pH), chemical oxygen demand (COD), ammonia nitrogen (NH$_3$-N) and oil indicators exceeding the standard. Jiang et al. [3] selected 7 highway tunnels under construction in Chongqing for wastewater sampling, and found that the main pollutants were suspended solids (SS) and the pH value exceeded the standard; Liu et al. [4] found that the main pollutants of construction wastewater in the entrance section of Tianmu Mountain tunnel are suspended solids (SS) and pH exceeding the standard, and the wastewater also contains heavy metals due to special rock stratum reasons; Ru [5] investigated typical railway tunnels in southwest, South China and Northwest China. The results showed that suspended solids (SS) were the main pollutants, and the pH value exceeded the standard, while COD and petroleum were non main pollutants.

On the whole, the main problem of the construction wastewater produced by the tunnel constructed by drilling and blasting method is that the SS concentration and pH value exceed the standard, but this cannot completely summarize the water quality characteristics of the wastewater produced by the tunnel constructed by drilling and blasting method. The quality of wastewater produced by different tunnels may vary, but the process of producing various pollutants is the same, because the drilling and blasting construction is a construction cycle in which each process is carried out in turn, and the change mode of pollutant concentration in the generated wastewater also shows the characteristics of periodic change. At present, the research on the pollutants of drilling and blasting construction wastewater mainly focuses on the types of pollutants, and there is less analysis on the change mode of pollutant concentration in each stage of construction.

In addition, the quality of wastewater produced in different construction stages is often different, and the water treatment methods for different stages cannot be generalized. In order to effectively deal with the wastewater treatment in different construction stages, it is necessary to study the water quality in different construction stages.

Therefore, based on the Hengwu tunnel on the connecting line of Kaihua section of national highway 351, this paper studies the change characteristics of wastewater quality during tunnel construction. By sampling the wastewater produced by the tunnel during the construction period, the causes of various pollutants in the wastewater and the change mode of the types and concentrations of various pollutants in the tunnel construction process are analyzed, and the pollution degree of each construction wastewater obtained by sampling is evaluated by the set pair analysis method, which lays a foundation for selecting a more appropriate treatment process.
2. Project Overview

2.1. Tunnel Profile

Kaihua, the location of Hengwu tunnel, is located at the source of Qiantang River. It is an important ecological barrier in Zhejiang Province and even East China. The location of Hengwu tunnel is shown in Figure 1.

Hengwu tunnel is a single tunnel and two-lane tunnel with a total length of 2.1 km. The tunnel site is in hilly landform, with mountain elevation between 150 m-360m, relative height difference of 210 m and topographic slope of about 30°-40°. The lithology is mostly Silurian Kangshan formation sandstone, the groundwater type is mainly bedrock fissure water, and the hydrogeological conditions are relatively simple.

The tunnel construction method adopts drilling and blasting method. Except that the portal section is grade V surrounding rock, the surrounding rock of the tunnel body section is mainly grade IV and III surrounding rock. The grade V surrounding rock section is excavated after advanced pre support. The pre support method of pipe shed combined grouting is adopted for the portal section, the pre support method of small conduit combined grouting is adopted for other sections of the tunnel, and the excavation adopts core retaining ring excavation. The relatively broken surrounding rock section is excavated by side wall heading method, manual excavation or blasting excavation. The grade IV surrounding rock is excavated by positive bench. Half section method is adopted for class III surrounding rock, and full section excavation is adopted for hard rock sections with relatively complete surrounding rock. The wastewater generated during the construction is pumped to the sedimentation tank outside the portal step by step through the water pump. The transverse section of Hengwu tunnel is shown in Figure 2.
2.2. Drilling and Blasting Construction Process

Drilling and blasting construction is a construction process that includes several sequential processes and keeps circulating, it usually includes the following construction processes [6]:

- First, curtain grouting shall be carried out;
- Second, drill holes, charge explosives and blast;
- Third, solid residue from blasting is transported out of the tunnel;
- Forth, the excavated part of the tunnel shall be initially supported;
- Finally, the secondary lining is constructed in the tunnel.

The pollutants in the wastewater generated by construction also come from these construction processes. The gathering place of waste water on the construction site is shown in Figure 3.

3. Types and Concentration Changes of Wastewater Pollutants during Construction

3.1. Sources of Pollutants in Wastewater

- Suspended solids

Most of the suspended solids in the tunnel construction wastewater come from the dust generated by the tunnel working face. There are three main sources:

(a) Dust in rock mass fissures generated due to geological processes and geological changes before excavation.
In the process of drilling and blasting construction, the dust produced by rock explosion under the action of explosives.

Dust escaping from gravel due to friction and collision during transportation.

In addition, when materials such as cement mortar and concrete leaked during shotcrete or grouting are mixed into the inflow water body, wastewater with high suspended solids concentration will also be formed. Among them, blasting dust and process dust account for about 80%-90% of dust, while dust from other sources accounts for only 10%-20% [7].

Nitrogen containing pollutants

The nitrogen-containing pollutants in the tunnel construction wastewater by drilling and blasting method mainly come from the explosives used in the blasting process. The nitrogen-containing residue produced by explosive explosion enters the water body near the tunnel working face, making the wastewater contain nitrogen-containing pollutants. The explosive used in this tunnel is No. 2 rock emulsion explosive, in which the oxidant ammonium nitrate is the main component of emulsion explosive. The explosive reaction of ammonium nitrate generates NO₂, and the reaction formula is shown below:

\[ \text{NH}_4\text{NO}_3 \rightarrow \frac{3}{4}\text{N}_2 + 2\text{H}_2\text{O} + \frac{1}{2}\text{NO}_2 \]  (1)

NO₂ gas dissolves in water to generate nitric acid. The reaction formula is shown below:

\[ \text{NO}_2 + \frac{1}{3}\text{H}_2\text{O} \rightarrow \frac{2}{3}\text{HNO}_3 + \frac{1}{3}\text{NO} \]  (2)

In practical engineering, the explosive used in each blasting cannot completely explode, and the residual ammonium nitrate exists in the form of ammonia nitrogen (NH₃-N). Therefore, the pollutants produced by emulsion explosive explosion are mainly nitrate nitrogen and ammonia nitrogen. In addition, due to the relatively closed construction environment of the tunnel, NO₂ and residual NH₄NO₃ produced after blasting enter the construction wastewater under the action of water seepage or dust reduction water to form nitrogen-containing pollutants.

Petroleum pollutants

The mechanical equipment used in the construction process, such as excavation equipment, drilling equipment, slag transportation machinery, shotcrete and anchor grouting machinery, will produce varying degrees of oil pollution. When this oil pollution enters the ponding near the construction face, it will form wastewater containing petroleum pollutants.

pH value

The cement water glass solution used in the grouting process, as well as the cement mortar, concrete and other pollutants used in the shotcrete and formwork process enter the tunnel water inflow, resulting in the increase of the pH value of the tunnel construction wastewater.
Chemical oxygen demand

Generally, there is no large amount of organic matter discharged during the construction of the tunnel. The pollutants in the wastewater are mainly inorganic pollutants, and the main organic matter is petroleum substances such as lubricating grease leaked during the construction. Other reducing inorganic substances contained in rock powder also have a certain impact on the COD of wastewater.

Phosphorus containing pollutants

Phosphorus containing pollutants are an important cause of water eutrophication. Phosphorus containing pollutants are rarely produced during tunnel construction.

3.2. Sampling at Different Stages of Tunnel Construction

A 500 ml plastic bottle and a 500 ml glass bottle are taken for each sampling. The water sample in the plastic bottle can be used to detect the contents of ammonia nitrogen, total phosphorus, chemical oxygen demand, pH value and suspended solids in the wastewater; the water sample in the glass bottle can be used to detect the content of petroleum in wastewater.

In order to analyze the variation characteristics of wastewater quality in different construction stages, wastewater sampling shall be conducted within 16 hours from drilling, blasting, slag discharge to initial support of a certain section of tunnel. The background water sample is taken from the upstream river of the entrance section of Hengwu tunnel. Some water samples are shown in Figure 4.

3.3. Wastewater Quality Analysis

As can be seen from Table 1, the wastewater discharged during the construction period can only be discharged to the nearby surface water body after being treated to reach the first-class standard, which refers to GB8978-1996 integrated wastewater discharge standard [8]. The discharge standard of tunnel construction wastewater is shown in Table 2.

Of all samples, Sample 1 was background water sample, Sample 2 was taken from the drilling stage before tunnel blasting, Sample 3 was taken from the post blasting stage,
Samples 4 and 5 were taken from the tunnel slag removal stage respectively, Samples 6 and 7 were taken from the shotcrete stage of the tunnel.

### Table 1. Water quality of wastewater from Hengwu tunnel construction (Unit: pH value is dimensionless, others are mg/L).

<table>
<thead>
<tr>
<th>Sample number</th>
<th>pH</th>
<th>COD</th>
<th>Suspended solid</th>
<th>Ammonia nitrogen</th>
<th>Total phosphorus</th>
<th>Petroleum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.83</td>
<td>34</td>
<td>18</td>
<td>0.039</td>
<td>0.029</td>
<td>&lt;0.06</td>
</tr>
<tr>
<td>2</td>
<td>11.41</td>
<td>44</td>
<td>280</td>
<td>1.32</td>
<td>0.25</td>
<td>2.36</td>
</tr>
<tr>
<td>3</td>
<td>11.49</td>
<td>48</td>
<td>121</td>
<td>0.061</td>
<td>0.56</td>
<td>4.16</td>
</tr>
<tr>
<td>4</td>
<td>11.50</td>
<td>39</td>
<td>280</td>
<td>1.32</td>
<td>0.25</td>
<td>2.36</td>
</tr>
<tr>
<td>5</td>
<td>11.35</td>
<td>71</td>
<td>1370</td>
<td>0.236</td>
<td>0.486</td>
<td>2.12</td>
</tr>
<tr>
<td>6</td>
<td>12.09</td>
<td>495</td>
<td>6990</td>
<td>0.913</td>
<td>0.486</td>
<td>2.12</td>
</tr>
<tr>
<td>7</td>
<td>12.02</td>
<td>194</td>
<td>3390</td>
<td>3.01</td>
<td>0.750</td>
<td>2.16</td>
</tr>
</tbody>
</table>

### Table 2. Wastewater discharge standard.

<table>
<thead>
<tr>
<th>Detection index</th>
<th>pH</th>
<th>COD</th>
<th>Suspended solid</th>
<th>Ammonia nitrogen</th>
<th>Total phosphorus</th>
<th>Petroleum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge standard</td>
<td>6-9</td>
<td>≤100</td>
<td>≤70</td>
<td>≤15</td>
<td>≤1</td>
<td>≤10</td>
</tr>
</tbody>
</table>

Among the six indexes tested, total phosphorus and petroleum did not exceed the limit value of the specification in the main construction stage. It can be considered that these two indexes are not the main pollutants of tunnel construction wastewater. Among the four indicators exceeding the emission standards, the pH value and suspended solids concentration indicators exceed the emission standards in all stages, while the chemical oxygen demand and ammonia nitrogen indicators exceed the emission standards only in specific stages.

Among them, the content of petroleum substances is significantly higher than that in other stages before blasting and slagging stage. The reason may be that the oil pollution generated by the drilling equipment in the pre blasting stage enters the construction wastewater, and the petroleum substances leaked by the slag truck enter the construction wastewater in the slagging stage.

The pH value of construction wastewater is higher than the discharge standard, and the construction wastewater is obviously alkaline. It is mainly because the pollutants such as cement mortar and concrete used in shotcrete in the initial support stage enter the tunnel water inflow and construction water to form alkaline construction wastewater.

The concentration of suspended solids in construction wastewater exceeds the discharge standard in all stages, especially in the initial support stage. In the pre blasting stage, due to the influence of drilling and cleaning processes, the concentration of suspended solids in construction wastewater in this stage is high. With the blasting of rock stratum, the dust produced by blasting increases rapidly in a short time and enters the wastewater in the tunnel, and the concentration of suspended solids in the wastewater also increases. In the later slag discharge stage, the crushed stone produced by blasting will also escape dust due to friction, collision and other effects during transportation, which will also lead to the increase of suspended solids concentration in construction wastewater at this stage. In particular, the concentration of suspended solids in the wastewater sample obtained in the initial branch stage is abnormally high, and the color of the water sample is gray and the water quality is turbid. The suspended solids in the wastewater at this stage are mainly composed of cement mortar, concrete and other
substances collected near the working face during shotcrete, resulting in extremely high suspended solids concentration measured in the sample.

The concentration of ammonia nitrogen in construction wastewater is higher after blasting and slag discharge stage, because NO$_2$ and residual ammonium nitrate produced in a short time after rock blasting enter the wastewater of the working face. The concentration of nitrogen-containing pollutants increases rapidly at this stage and forms a concentration peak. With the progress of subsequent stages, the concentration decreases continuously.

The concentration of chemical oxygen demand in construction wastewater is only higher than the discharge standard at the stage of shotcrete construction. During the construction of shotcrete, the COD concentration of construction wastewater is high, which may be affected by two aspects. First, due to the specific surface area properties and surface energy, the surface of suspended solids and particles usually adsorbs other chemical substances, so the concentration of suspended solids will have an impact on the COD concentration of wastewater. Generally, there is a certain positive correlation between COD of tunnel construction wastewater and suspended solids concentration. When adverse conditions are encountered, the increase of wastewater suspended solids concentration is accompanied by the increase of COD [9]. It has been found that there is a good correlation between SS concentration and TP and COD concentration in a tunnel construction wastewater, and the correlation coefficients between them reach 0.993 and 0.984 respectively [10]. Therefore, due to the extremely high concentration of suspended solids in the initial stage, the COD value in the corresponding wastewater is also high; Second, the construction wastewater in the initial support stage is polluted by petroleum substances such as mechanical lubricating oil, which increases the COD concentration of the wastewater.

According to the above analysis process, the change mode of pollutant concentration in drilling and blasting construction wastewater can be briefly summarized, as shown in Figure 5. Stage 1 represents the drilling stage before tunnel blasting, Stage 2 represents the post blasting stage, Stage 3 represents the tunnel slag removal stage, Stage 4 represents the shotcrete stage.

![Figure 5. Variation model of pollutant concentration in drilling and blasting construction wastewater.](image-url)
According to the sequence of procedures, within a period of time after rock blasting, the incompletely exploded ammonium nitrate enters the wastewater near the construction face, and the ammonia nitrogen concentration in the wastewater rises rapidly and reaches the peak first. Due to drilling and flushing, the concentration of suspended solids is high in the initial stage. In the subsequent slag discharge and initial support process, rock powder, mortar and other substances enter the wastewater near the working face, and the concentration of suspended solids increases significantly and reaches the peak in the initial support stage. The concentration of COD is affected by the use of mechanical equipment and the concentration of suspended solids, so its concentration growth stage is roughly the same as that of suspended solids.

4. Evaluation of Wastewater Pollution Degree Based on Set Pair Analysis

4.1. Set Pair Analysis Principle

Set pair analysis is a systematic theoretical method to deal with uncertain problems. The so-called set pair refers to the pair composed of two sets with certain connection. The basic idea of set pair analysis is to establish the same, different and opposite connection degree expression of the two sets under a certain problem background [11]. For the evaluation of construction wastewater quality based on set pair analysis, firstly, a set pair is established between the evaluation index concentration and the evaluation index. For a sample, if there are \( N \) evaluation indexes, of which \( S \) measured indexes are better than the evaluation indexes, \( P \) measured indexes are worse than the evaluation standards, and \( F \) measured indexes are not measured or lack of comparison, then the expression of the connection degree of the sample is as follows:

\[
\mu = \frac{S}{N} + \frac{F}{N} \cdot i + \frac{P}{N} \cdot j = a + bi + cj
\]

where, \( \mu \) is the degree of connection, \( i, j \) is the difference uncertainty and opposition mark respectively; \( a = \frac{S}{N}, b = \frac{F}{N} \) and \( c = \frac{P}{N} \) are called identity degree, difference uncertainty and opposition degree in turn.

According to the definition, \( a, b \) and \( c \) meet the normalization condition \( a + b + c = 1 \). At the same time, \( a, b \) and \( c \) are comprehensive descriptions of the same problem from different angles, so there is a relationship of mutual connection, restriction and transformation among the three. In the actual water quality evaluation, because the water contains different components, their contents may belong to different grades, which can judge the degree of water pollution according to the size relationship of the three. The closer \( a \) value is to 1, the closer the water quality is to the natural state; The larger the value of \( b \), it indicates that the polluted components have entered the water body; The larger the value of \( c \), the higher the degree of water pollution.

4.2. Evaluation of Pollution Degree of Tunnel Construction Wastewater in Different Stages

The formulation of wastewater quality evaluation index standard refers to GB8978-1996 integrated wastewater discharge standard. In this paper, the pollution degree of
construction wastewater is divided into grade I, grade II and grade III, corresponding to mild pollution, moderate pollution and serious pollution respectively. The closer \( a \) value is to 1, the closer the wastewater is to grade I wastewater, and its pollution degree is low during construction; The larger the \( c \) value, the closer the wastewater is to grade III wastewater, which is greatly affected by the construction process.

Specific classification standards are in Table 3.

Table 3. Evaluation standard for pollution degree of construction wastewater (Unit: mg/L).

<table>
<thead>
<tr>
<th>Pollution index</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia nitrogen</td>
<td>0-15</td>
<td>16-20</td>
<td>21-25</td>
</tr>
<tr>
<td>Chemical oxygen demand</td>
<td>0-100</td>
<td>101-150</td>
<td>151-500</td>
</tr>
<tr>
<td>Suspended solids</td>
<td>0-400</td>
<td>401-3000</td>
<td>3001-7000</td>
</tr>
</tbody>
</table>

The connection degree of construction wastewater in different stage is calculated according to the formula.

Sample 2: \( \mu_2 = \frac{2}{3} + \frac{1}{3} i + 0 j = 0.67 + 0.33i + 0j \) \( (4) \)

Sample 3: \( \mu_1 = \frac{2}{3} + 0 j + \frac{1}{3} j = 0.67 + 0j + 0.33j \) \( (5) \)

Sample 4: \( \mu_4 = \frac{2}{3} + \frac{1}{3} i + 0 j = 0.67 + 0.33i + 0j \) \( (6) \)

Sample 5: \( \mu_5 = \frac{2}{3} + \frac{1}{3} i + 0 j = 0.67 + 0.33i + 0j \) \( (7) \)

Sample 6: \( \mu_6 = \frac{3}{4} + 0 i + \frac{2}{3} j = 0.33 + 0i + 0.67j \) \( (8) \)

Sample 7: \( \mu_7 = \frac{1}{3} + 0 i + \frac{2}{3} j = 0.33 + 0i + 0.67j \) \( (9) \)

By comparing the degree of identity, degree of difference and degree of opposition in the above formulas, it can be seen that the pollution degree of construction wastewater produced in slag discharge stage and pre blasting stage is relatively light; The pollution degree of construction wastewater generated in the initial support stage is the most serious.

Taking the drilling stage (Sample 2) as an example, the correlation expression of the component content of the three evaluation indexes relative to the water quality classification standard is as follows:

\[ \mu_{2,COD} = 1 + 0i + 0j \] \( (10) \)
\[ \mu_{2,\text{SS}} = \frac{3000 - 492}{3000 - 400} + \frac{492 - 400}{3000 - 400} \cdot i + 0.96 + 0.04i + 0 j \]  

(11)

\[ \mu_{2,\text{NH}_3} = 1 + 0i + 0j \]  

(12)

After averaging the three indicators, the following connection degree is obtained.

\[ \mu = 0.99 + 0.01i + 0j \]  

(13)

The connection degree of other water samples can be obtained by the same calculation method.

\[ \mu_3 = 0.67 + 0.24i + 0.09j \]  

(14)

\[ \mu_4 = 0.77 + 0.23i + 0j \]  

(15)

\[ \mu_5 = 0.88 + 0.12i + 0j \]  

(16)

\[ \mu_6 = 0.33 + 0i + 0.67j \]  

(17)

\[ \mu_7 = 0.33 + 0.59i + 0.08j \]  

(18)

The coefficient in the above six formulas is the same degree that different wastewater belongs to different levels of wastewater. For example, the construction wastewater generated in the drilling cleaning stage is 99% of the grade I wastewater. The construction wastewater in the post blasting stage is 67% of the grade I wastewater. By comparing the same degree of the above types, it can be seen that the pollution degree of each wastewater sample is as follows from small to large: Sample 2, Sample 5, Sample 4, Sample 3, Sample 7, Sample 6.

At the same time, the pollution degree of wastewater samples can also roughly reflect the impact of different construction stages on wastewater quality, the influence degree from small to large is drilling cleaning stage, slag discharge stage, post blasting stage and initial support stage.

5. Conclusions

In this paper, the wastewater in each construction stage of Hengwu tunnel is sampled, and the following conclusions are drawn according to the test results:

- The main problems of the construction wastewater of Hengwu tunnel are the high pH value, the high concentration of suspended solids, and the high concentration of chemical oxygen demand and ammonia nitrogen in some stages. Petroleum and total phosphorus are not the main pollutants.
- The pollutant concentration of drilling and blasting construction wastewater has its regular change mode with the continuous circulation of construction process.
In a period of time after blasting, the contents of suspended solids and ammonia nitrogen rise rapidly. The concentration of ammonia nitrogen first reaches the peak and gradually decreases in the subsequent stages. The content of suspended solids reaches the peak in the initial branch stage, and the growth stage of chemical oxygen demand is roughly the same as that of suspended solids concentration. The pH value changes little during construction and is always higher than the discharge standard.

- The impact of different construction stages on construction wastewater is different. The pollution degree of construction wastewater produced in the initial support stage of Hengwu tunnel is the most serious, and the pollution degree of construction wastewater before blasting is the least.
- The main components and pollution degree of pollutants in the wastewater in different construction stages of the tunnel are different. According to the main pollutants to be treated in different stages, natural sedimentation, flocculation sedimentation, mechanical treatment and other methods can be comprehensively used to improve the wastewater treatment efficiency. The discharge direction of the treated wastewater should be reasonably planned and recycled to the greatest extent.

References