A Study on the Process Regulation of Dairy Wastewater Treatment Based on the on-line Monitoring System

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Abstract. In order to avoid the pollution of dairy product processing wastewater and the waste of online water quality monitoring data, a research on the regulation technology of dairy product processing wastewater treatment based on the online monitoring data of effluent water quality was carried out. This experiment is based on a UASB-A/O treatment process pilot scale of a dairy processing wastewater treatment station, and the relevant kinetic parameters are measured to determine the correlation between the effluent water quality indicators and process operating parameters such as sludge load and sludge age. Use this relationship to guide the process parameter adjustment and improve the effluent water quality. The research results show that there is a good correlation between effluent Se and external operating parameters such as sludge load, sludge age and DO, and the optimal control range of sludge load is 0.0766~0.0998 kgBOD/(kgMLSS·d); The optimal control range of sludge age is 33~38 d. And when the sludge concentration (MLSS) changes between 2800~3500 mg/L, the effluent water quality is better. According to the obtained process control method, the pilot plant is adjusted accordingly, and the effect is significant. Water quality indicators such as effluent Se and ammonia nitrogen change significantly, and the effect of nitrogen and phosphorus removal becomes better, which meets the needs of practical engineering.

1. Introduction

The automatic water quality monitoring system can measure the water quality status in an accurate and dynamic manner with multiple indicators in real time. It can also conduct centralized management of the monitored data so as to maximize the informatization level of the monitoring and laboratory analysis of water quality [1].

Under the national compulsory requirements, enterprises often take passive moves in terms of building water quality online monitoring systems in their wastewater treatment stations [2]. The data obtained by the online monitoring instrument is uploaded to the competent government department to distinguish whether the water meets the standard, with no further processing measures, resulting in the waste of data related to the operation of wastewater treatment facilities. In fact, by processing and analyzing these data, we can obtain the correlation between the quality of the wastewater after treatment and the operating parameters. Based on this correlation and a process control feedback mechanism, we can establish a management platform of wastewater treatment, which can provide enterprises with appropriate decision-making and technical support to a certain extent.
In this test, we established a pilot test device based on the treatment process of a sewage treatment station of a dairy processing enterprise in Chongqing City to measure the main pollutants such as COD, NH₃—N, BOD, and TP in the effluent and to determine various kinetic parameters. Based on that, we explored the relationship between the sludge load, sludge retention time (SRT) and other external operating parameters, and set up a regulation mechanism so as to improve the quality of effluent water and stabilize the processing operation.

2. Test material and method

2.1 Test device

The pilot test device is based on the existing sewage treatment station of a dairy processing enterprise in Chongqing City. It is designed using the UASB-A/O and is made of plexiglass with a design flow rate of 0.15m³/d. The test involves only biochemical treatment and no pre-processing or in-depth processing. The technological process is shown in Figure 1.

Figure 1. UASB-A/O process flow chart

The design parameters of UASB-A/O pilot test are shown in Table 1.

Table 1. UASB-A/O Design parameter table

| Item                        | Anoxic pool | Aeration tank |
|-----------------------------|-------------|---------------|
| Hydraulic retention time (HRT)/d | 0.416       | 1.467         |
| Effective volume/m³         | 0.062       | 0.220         |
| Biosolids retention time/d  |             | 35            |
| MLSS/(mg/L)                 |             | 3500          |

The kamoer intelligent speed regulation metering pump was used as the pump to press water into the bottom of the UASB tank. The return of nitrification liquid and sludge was realized using peristaltic pumps with different flow rates, and the return of others adopted gravity flow. The UASB tank was equipped with a vertical mixer to control the stirring speed so that the thickness of sludge bed can be stable. At the same time, the facultative tank was also equipped with a mixer for uniformly mixing nitrification reflux, sludge reflux and UASB reactor effluent. The aerobic tank used an air pump for aeration and it was connected with a microporous aeration tube to ensure an even and stable aeration effect.

2.2 Quality of influent water and analytical method

The raw sewage emitted by the sewage treatment station of the dairy processing enterprise in Chongqing City was used as the influent. Its quality is shown in the following table.

Table 2. The quality characteristics of dairy wastewaters

| CODcr (mg/L) | Ammonia nitrogen (mg/L) | Total nitrogen (mg/L) | Total phosphorus (mg/L) | pH         |
|--------------|-------------------------|-----------------------|-------------------------|------------|
| 1000~2000    | 100~180                 | 120~200               | 14~30                   | 6~8        |
During the test, we measured the conventional water quality indicators, including COD, BOD, NH₄⁺—N, TN, TP, DO and pH. The methods for testing COD, BOD, NH₄⁺—N, TN, TP were all taken from Methods for Water and Wastewater Analysis and Detection (Fourth Edition), and the values of DO and pH were measured using a dissolved oxygen meter and a pH meter, respectively.

2.3 Test method

The sludge in the reactor was taken from the sewage processing station of a dairy processing enterprise in Chongqing City, and the system reached a stable state after the water quality indicators such as MLSS, SRT, and DO were debugged. After measuring COD, BOD, MLSS, TN, TP and other water quality indicators under the stable condition, we can determine system dynamics parameters based on the analysis of the massive amount of data.

When the A/O system is under operation, factors such as sludge retention time, sludge load, DO, circulation ratio, MLSS have an important impact on the effluent quality [3]. In order to obtain good effluent water quality, this test mainly regulated the above external parameters. By studying the relationship between effluent BOD and sludge load, sludge retention time and other related technical indicators, we can obtain the main technological parameters for regulation and for related regulation methods.

3. Test results

3.1 Measurement of kinetic parameters

After the system was debugged, MLSS was stable at 2800~4000mg/L, and the nitrate reflux ratio was stable at about 180%. The DO of the UASB pool was less than 0.2 mg/L, that of the anoxic pool was less than 0.5 mg/L, and that of the aerobic pool was stable between 2.0~4.0 mg/L.

According to the Monod equation, Lawrence-McCarty equation, and the basic equation of microbial growth [4], after substituting operating parameters such as effluent water quality during the stable reactor operation, sludge concentration, sludge SRT, and hydraulic residence time (HRT), we can obtain the kinetic parameters $r_{max}$ (maximum substrate degradation rate) = 0.9091, $K_s$ (saturation constant) = 157.82 mgBOD/L, $Y$ (yield coefficient) = 0.5492d⁻¹, $K_d$ (ratio Constant) = 0.0226d⁻¹, and $\mu_{max}$ (Maximum specific proliferation rate of microorganisms) = 0.4993d⁻¹.

3.2 Analysis of the relationship between effluent water quality and operating parameters

3.2.1 Relationship between effluent water quality and sludge load

Sludge load is an important factor affecting the degradation of organic pollutants and the growth of activated sludge, and it is also directly related to the expansion of activated sludge [5]. Therefore, the sludge load is an important controlled parameter during sewage treatment.

According to the Lawrence and McCarty model, the sludge load can be calculated using [6]:

$$S_e = \frac{(F/M)K_s}{r_{max} - (F/M)}$$

(2.1)

In the formula, $S_e$ represents the concentration of the organic substrate; $(F/M)$ represents the ratio of the amount of organic pollutants to the amount of activated sludge; $K_s$ represents the saturation constant; $r_{max}$ represents the maximum substrate degradation rate.

After fitting and analyzing the measured BOD and sludge load of the effluent using the origin data analysis software, we can obtain the relationship between BOD and sludge load.

Fit $F/M$ to the measured $S_e$, and the result is shown in Figure 2.
The fitted curve equation obtained in Figure 2 is:

\[ S_e = 213.952 \left( \frac{F}{M} \right) - 2.47 \quad R^2 = 0.976 \quad (2.2) \]

The SPSS data analysis software was used to perform a single factor test on the measured \( S_e \) and fitted \( S_e \) values. The result showed that at a confidence of 0.05, there was no significant difference between the measured and fitted values, and the fitting effect was good.

Therefore, the relationship between the effluent BOD and sludge load can be expressed using Formula (2.2). Within acceptable limits, when the sludge load increased, the effluent BOD increases accordingly, and vice versa. Effluent BOD changed with sludge load.

Since effluent BOD cannot exceed 20 mg/L, it can be seen from Formula (2.2) that when \( S_e < 20 \) mg/L, the sludge load was \( F/M < 0.1050 \) kgBOD/(kgMLSS·d). Therefore, the sludge load \( F/M \) should be lower than 0.105 kgBOD/(kgMLSS·d). Since it is necessary to reserve some reaction time for early warning, the upper limit warning value of the sludge load should be \( F/M < 0.0945 \) kgBOD/(kgMLSS·d) (take 90% of the actual value).

2 Relationship between effluent \( \text{NH}_4^+ - N \) and sludge load \( F/M \)

Figure 3 shows the changing curve of effluent \( \text{NH}_4^+ - N \) and sludge load at the same time point every day. The sludge load is influenced greatly by the influent water quality, but less by other factors such as the influent amount and sludge concentration. It can be seen from the figure that effluent \( \text{NH}_4^+ - N \) generally increased with increasing sludge load \( F/M \), but the change was relatively lagging [7].
autotrophic bacteria cannot become the dominant species, thereby affecting the nitrification reaction, lowering the conversion efficiency of \( \text{NH}_4^+ \) — N to nitrate nitrogen in the aerobic pool, and increasing \( \text{NH}_4^+ \) — N in the effluent. It is worth emphasizing that in the sewage treatment station where there was continuous and stable water inflow, the change in sludge load was mainly due to the change in water quality.

In fact, when the above sludge load upper limit \( F/M < 0.0945 \text{ kgBOD/(kgMLSS·d)} \) was adopted, the ammonia nitrogen concentration of the effluent was far lower than the 15 mg/L as required.

(3) Relationship between effluent TP and sludge load \( F/M \)

\[ \eta_{TP} = -1123090 \exp \left( - \frac{F}{0.0045} \right) + 0.9804 \quad R^2 = 0.9239 \quad (2.3) \]

It can be seen from Figure 4 that when the sludge load was within 0.080~0.095 kgBOD/(kgMLSS·d), the TP removal rate changed little with the sludge load; when the sludge load was below 0.080 kgBOD/(kgMLSS·d), the TP removal rate decreased rapidly, but was still high at this time. When the sludge load is maintained above 0.073 kgBOD/(kgMLSS·d), the TP removal rate reached 90%. But when the TP removal rate is relatively stable when the sludge load is higher. Therefore, when a certain reaction interval is reserved, the lower limit of the sludge load shall be \( F/M > 0.0803 \text{ kgBOD/(kgMLSS·d)} \) (take 110% of the actual value).

To sum up, the optimal control range of sludge load is within 0.0803~0.0945 kgBOD/(kgMLSS·d), which can be converted to effluent BOD as within 14.71 ~ 17.75 mg/L.

Therefore, the specific situation of changing effluent quality caused by the change of sludge load is as follows:

1) When the increase of the influent water concentration caused the sludge load to exceed the upper limit of the optimal control interval, the effluent BOD exceeded 17.75 mg/L, TP removal rate was high, the effluent TP was high, and the ammonia nitrogen was also high (generally lower than 15 mg/L).

2) When the sludge load exceeded the lower limit of the optimal control interval due to the decrease of the influent water quality, the effluent BOD was lower than 14.71 mg/L, the TP removal rate was low, the effluent TP might exceed the effluent index, and the effluent ammonia nitrogen concentration was relatively low.

3.2.2 Relationship between effluent water quality and sludge retention time

(1) Relationship between effluent Se and sludge retention time
When the sewage activated sludge treatment method is adopted, the population structure, activity, and quantity of the microorganisms that make up the micelles are vital to the pollutant removal [8] [9]. The sludge retention time has a profound impact on the nitrogen and phosphorus removal, and it is also an important parameter for the control system for sewage treatment.

According to the Lawrence-McCarty model, the relationship between effluent and sludge retention time can be shown as [6]:

$$S_e = \frac{K_s(1 + K_d\theta_c)}{\theta_c(Yr_{\text{max}} - K_d) - 1} \quad (2.4)$$

In the formula, $S_e$ represents the concentration of the organic substrate; $\theta_c$ represents the sludge retention time (SRT); $K_s$ represents the saturation constant; $r_{\text{max}}$ represents the maximum substrate degradation rate; $Y$ represents the yield coefficient, $K_d$ represents the proportional constant.

The fitted value was calculated using Formula 2.4, and the SPSS data analysis software was used to perform the single factor test on the measured and the fitted $S_e$ values. The result showed that the difference between the two values was not significant at the confidence level of 0.05.

In summary, the relationship between the effluent BOD and the sludge retention time can be expressed using Formula 2.5:

$$S_e = \frac{3.567\theta_c + 157.82}{0.4767\theta_c - 1} \quad (2.5)$$

Since effluent BOD cannot exceed 20 mg/L, it can be seen from Formula 2.5 that when $S_e<20$ mg/L, the sludge retention time was $\theta_c>29.80$ d. Therefore, the sludge retention time $\theta_c$ should be higher than 29.80 d. In order to reserve a certain reaction time for early warning, the lower limit of the optimal control interval of sludge retention time should be $\theta_c>32.78$ d (take 110% of the actual value).

② Relationship between effluent NH$_4^+$-N, TN, TP and sludge retention time

![Figure 5. The changing curve of SRT, NH$_4^+$-N, TN, TP and sludge retention time](image)

Figure 5 shows the relationship between various indicators of the effluent and sludge retention time. As the amount of remaining sludge decreased, the sludge retention time gradually increased. The sludge retention time can be roughly divided into three stages, as shown in the figure. As the sludge retention time increased, the effluent TP did not change much at the beginning. But when the sludge retention time increased to 40.3d, the effluent TP began to increase significantly, which may be because that the system mainly removed phosphorus by discharging the residual sludge; when the sludge retention time increased, the residual sludge discharge decreased, and so was the total phosphorus discharge, leading to TP accumulation in the system and an increase in effluent TP. Overall, the total nitrogen increased slightly with the increase of sludge retention time, and the ammonia nitrogen decreased with the increase of sludge retention time. That is because as the sludge retention time increased, the nitrobacterium in the nitrification reactor increased in quantity, which was conducive to the progress of the nitrification reaction, leading to less ammonia nitrogen. However,
since the total nitrogen was mainly removed through denitrification, the effect of denitrification was not obvious.

Therefore, the sludge retention time shall be controlled at 33 to 38 days, within which the overall effluent water quality can be overall good. But when sludge retention time changed from 33 to 38 days, effluent $S_e$ did not change much, so the range can be widened to 33 to 40 days

In summary, the changes in effluent water quality caused by changes in sludge retention time are as follows:

1) When the sludge retention time exceeded the upper limit of the optimal control interval (40 d), effluent $S_e$ and ammonia nitrogen were relatively low, and total phosphorus and total nitrogen were relatively high;

2) When the sludge retention time exceeded the lower limit of the optimal control interval (33 d), effluent $S_e$ and ammonia nitrogen were relatively high (effluent $S_e$ may exceed the standard). The total phosphorus and the total nitrogen were normal. If sludge retention time continued to decrease, then the effluent water quality might show an overall deterioration.

3.2.3 Relationship between effluent water quality and sludge concentration (MLSS)

1) Relationship between effluent $S_e$ and sludge concentration (MLSS)

When the sludge concentration (MLSS) changed but the influent water quality and quantity did not, there would be a change in sludge load. The specific engineering applications include:

$$\frac{F}{M} = N_s = \frac{Q S_0}{X V}$$

In the formula, $S_0$ represents the BOD concentration in the inlet of the aeration pool; $V$ represents the volume of aeration pool; $X$ represents the concentration of suspended solids in the mixed liquid; $Q$ represents the sewage flow.

The changing mechanism can refer to the relationship between effluent $S_e$ and sludge load.

2) Relationship between effluent $\text{NH}_4^-\text{N}$ and sludge concentration (MLSS)

When the sludge concentration was high, the sludge load was correspondingly low, and the carbon source required for sludge growth may be insufficient. Some sludge was used for endogenous breath, consuming too much DO, leading to low DO concentration in the aeration tank, thereby hindering nitrification and bringing up the effluent concentration[10]. On the other hand, the DO carried by the nitrification reflux was low in $\text{NH}_4^+\text{N}$ concentration, making the anoxic pond in a good condition, which was conducive to denitrification. When the sludge concentration was low, the total amount of nitrobacterium was relatively low, and nitrification is likewise limited, leading to higher effluent $\text{NH}_4^+\text{N}$ concentration. At the same time, the load resistance capacity is also low.

3) Relationship between effluent TP and sludge concentration (MLSS)

DO concentration of the aeration tank was low, which was not conducive to the excessive intake of phosphorus by phosphorus-accumulating bacteria, resulting in high effluent TP [11]. On the other hand, low concentration of DO in the aeration tank would lead to a lead low DO concentration in the sedimentation tank. If the sludge residence time in the sedimentation tank is not in time, it is easy to cause secondary release of phosphorus, leading to a high TP concentration. When the sludge concentration was low, the total amount of phosphorus-accumulating bacteria might be relatively low, which might also lead to high effluent TP.

It is found in the test that when MLSS varied within the range of 2500 ~ 4000 mg/L, it had little effect on effluent $S_e$; when MLSS was between 2800 ~ 3500 mg/L, the sludge load was moderate, nitrification and denitrification were efficient, phosphorus removal was satisfactory, and effluent $S_e$ also met the requirements.

In summary, when the sludge concentration (MLSS) in the aeration tank was low, effluent TP, $\text{NH}_4^+\text{N}$ and $S_e$ were high; when the sludge concentration (MLSS) in the aeration tank was high, effluent TP and $\text{NH}_4^+\text{N}$ were high and DO was slightly low. Low sludge load and low DO concentration led to moderate effluent $S_e$, which may be close to the upper limit of the water quality standard.
4. Control methods and effect prediction analysis

4.1 Control method

By summarizing the changes of effluent water quality caused by system changes, we can obtain the effluent water quality when feedback is needed, thereby forming a specific method of process control, which is shown in the following table.

Taking into account that it is necessary to reserve a certain reaction time for early warning, feedback indicators are generally taken as 90% of the upper limit or 110% of the lower limit. The value of ammonia nitrogen is taken according to Figure 3.

Table 3. The quality of effluent and feedback

| No. | TP (mg/L) | Ammonia nitrogen (mg/L) | Reason for feedback | Solution |
|-----|-----------|--------------------------|---------------------|----------|
| 1   | >0.45     | >2                       | ① Higher influent concentration leads to higher sludge load | Appropriately reduce the amount of water inflow; increase the amount of aeration to increase the internal reflux ratio; suggest that UASB may deteriorate |
|     |           |                          | ② Low MLSS in the aeration pool leads to higher sludge load | Appropriately increase sludge reflux; reduce residual sludge discharge. |
| 2   | >0.45     | >2                       | High MLSS in aeration tank leads to low sludge load | Appropriately increase the remaining sludge discharge and reduce the sludge concentration in the aeration tank. |
|     |           |                          |                    | Suggest that the sludge load is low, and be vigilant to operate in this state for a long time; increase the sludge load appropriately. |
| 3   | <0.45     | <0.5                     | Lower inlet water quality leads to lower sludge load | Appropriately increase the remaining sludge discharge, and slowly reduce the sludge retention time. |
| 4   | >0.45     | <0.5                     | Too high sludge retention time | Appropriately reduce the remaining sludge discharge and slowly increase the sludge retention time. |
| 5   | <0.45     | >2                       | Too low sludge retention time |                      |

4.2 Analysis of control effect

The purpose of this control is to assist the staff to optimize the process. On the one hand, the effluent water quality should be improved. Under the condition that the key indicators such as COD, BOD and NH₄⁺—N are good, the nitrogen removal rate and phosphorus removal effect should also be enhanced. On the other hand, the system shall consume less power and save operating costs.

Figure 6 shows the comparison between the results of the pilot test device before and after process control. The water quality of effluent continued to deteriorate from 3/05 to 3/09. At 3/09, effluent Se, ammonia nitrogen, and TP were 19 mg/L, 2.2 mg/L, and 0.46 mg/L, respectively. At this time, the first feedback conditions were met. It was detected that DO was generally greater than 2 mg/L. It can be seen from Table 3.1 that the possible reasons can be: ① higher water quality of the aeration tank leads to higher sludge load; ② low sludge concentrations in the aeration tank leads to higher sludge load. It was found that the water quality did not change much, but the sludge concentration in the aeration tank was around 2500 mg/L, which was not in the optimal range of 2800 ~ 3500 mg/L. Therefore, the sludge concentration is appropriately increased until it is within the optimum control range of 2800~3500 mg/L.
As can be seen from the figure, after the control started, the effluent water quality did not immediately change for the better, but grew worse. That is because of changes in effluent water quality feedback on the state of the process somehow lagged behind. On the next day after control, the effluent water quality improved markedly. After the control was completed, the effluent water quality continued to improve, and all water quality indicators returned to normal. Before control, the lowest effluent Se was 18 mg/L, and it became 16 mg/L and continued to decrease after control. Before control, the lowest effluent ammonia nitrogen was 1.2 mg/L, and it became 0.98 mg/L and continued to decrease after control. The above phenomena indicated that the process control helped to improve effluent Se and ammonia nitrogen and suppress the trend of TP increase. But the total phosphorus did not change much.

Figure 7 shows the comparison between the effects of nitrogen and phosphorus removal of the pilot test device before and after control. The average nitrogen removal efficiency before and after control was 69.52% and 74.86%, respectively (an increase of 5.34% after control). Due to the higher total nitrogen concentration in the aeration tank inlet, the control effect was relatively more obvious. The average phosphorus removal efficiency was 96.75% before control and 97.86% after control. The values did not change much after control, but they were relatively high.

In summary, after control, the water quality of effluent was optimized, the effluent Se and ammonia nitrogen were improved, the trend of TP increase was suppressed, and the effect of nitrogen and phosphorus removal was improved.
5. Conclusion

- When the system is stable, effluent Se and sludge load show a good correlation, the correlation coefficient is $R^2=0.976$, and the relationship is:

$$S_e = 213.952 \left( \frac{F}{M} \right) - 2.47$$

- SRT, as an important parameter for controlling the microbial population structure, quantity and metabolic mode of activated sludge micelles, also shows a good correlation with effluent $S_e$:

$$S_e = \frac{3.567 \theta_c + 157.82}{0.4767 \theta_c - 1}$$

- The optimal control interval of sludge load is within $0.0803 \sim 0.0945$ kgBOD/(kgMLSS·d), or $14.71 \sim 17.75$ mg/L when converted to effluent BOD; the optimal control interval of STR is $33 \sim 38$ d; when the sludge concentration (MLSS) is $2800 \sim 3500$ mg, the effluent water quality is better.

- Based on the change of effluent water quality, we can obtain the feedback mechanism for the process system, as shown in Table 3. Based on that, we can establish a dairy product wastewater process control system based on online monitoring.

- The controlling measures have a significant impact on the pilot test, with markedly improved water quality indicators such as effluent Se and ammonia nitrogen as well better nitrogen and phosphorus removal, meeting the needs of actual projects.

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