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Reuse rate of treated wastewater in water reuse system

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Abstract: A water quality model for water reuse was made by mathematics induction. The relationship among the reuse rate of treated wastewater(R), pollutant concentration of reused water(C_s), pollutant concentration of influent(C_0), removal efficiency of pollutant in wastewater(E), and the standard of reuse water were discussed in this study. According to the experiment result of a toilet wastewater treatment and reuse with membrane bioreactors, R would be set at less than 40%, on which all the concerned parameters could meet with the reuse water standards. To raise R of reuse water in the toilet, an important way was to improve color removal of the wastewater.

Keywords: water quality model; reuse rate; wastewater treatment; water reuse

Introduction

With the serious situation of water pollution and water shortage, wastewater as an unconventional water resource has been concerned by more and more people. The technologies for wastewater treatment and water reuse were developed and applied for toilet flushing, car washing, greening, makeup of cycle cooling water and underground water(Fan, 1995; Gu, 2002; Huang, 1998; Xu, 2002a; 2003; Yang, 2003).

It is well known that the removal rate of pollutants in wastewater treatment processes, i.e. activated sludge or bio-film processes, is less than 100%. The remained pollutants include coloring matter, total dissolved solid (TDS), excretion or extra cellular polymeric substance(EPS) of the microorganism, and so on. These substances are often the sources of color or COD in the treated water.

A basic characteristic of water reuse is that the treated water loops in the water reuse system, and the remained pollutants in the treated water therefore gradually accumulate with water reuse. If the circle times of the reused water in the water reuse system are up to a certain number, the concentration of one or more pollutants in the treated wastewater, such as color or TDS, will exceed the standards of reused water (Xu, 2002a; 2003; Yang, 2003). The phenomenon of pollutant accumulation in water reuse process is named as circulating concentration in this study.

The problems of circulating concentration in wastewater treatment and reuse processes are little mentioned. Few researches were focused on this problem and the impacts on the quality of reused water (Auer, 1993; Saqqar, 1992; Takashi, 1998; Xu, 2002b).

In order to find the way to solve the problem of the circulating concentration in wastewater reuse, the relationship among the reuse rate of treated waste water(R), the pollutant concentration of reuse water(C_s), the pollutant concentration of the waste water (C_0), the pollutant removal by the wastewater treatment process (E) and the standards of the reuse water were investigated in this study. The purposes of this study were to build a water quality model on changes of concentration of the pollutants in reused water and then recommend a proper R value.

1 System of wastewater treatment and reuse

A schematic diagram of the wastewater reuse system was conceived and given in Fig.1.

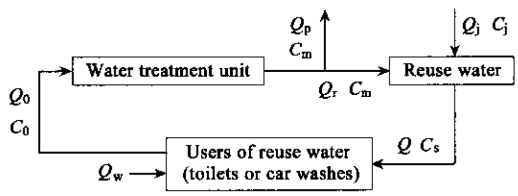

Fig.1 Flow diagram of a wastewater reuse system

In the schematic diagram, there are a wastewater treatment unit, which can be a biochemical process or a physic-chemical process, or a membrane bioreactor for wastewater treatment; a reused water tank in which the treated water mixed with part of fresh water is stored; and the facilities to reuse the water, that may be at a toilet or a car washing workshop. In the wastewater reuse system, the reused water is driven to the water demand facilities, where the wastewater is formed. The wastewater produced from facilities flows into the wastewater treatment unit where it is treated. Then, part of the effluent of wastewater treatment unit flows into the reused water tank, and part of it is discharged into the sewage. The purpose of discharging a part of the treated wastewater is to prevent huge accumulation of pollutants in the reused water. The water from reused water tank will be supplied to the water reuse facilities, where the pollutants will be added into the water and make it be the wastewater again. Then, it will be in to another cycle of treatment and reuse.

2 Water quality model for wastewater reclamation and reuse

2.1 The model deducted by mathematics induction

For making the water quality model, three assumptions are then set as follows: (1) both operation and E in the wastewater treatment unit are steady, and $E = \frac{C_0 - C_m}{C_0}$, $E < 100\%$; (2) $C_0 \times Q_0$ are the quantity of concerned pollutant added into the reused water at each circulation; (3) N denotes the circulation times in wastewater reuse system.

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The model was deducted by mathematics induction as follows:

At $N = 0$, the wastewater reuse system begins to operate. The reused water tank is filled with fresh water, and $Q_r = 0$, so that,

$$Q_0 = Q + Q_w = Q_{j0} + Q_w, \quad (1)$$

$$C_{m0} = C_0(1 - E) = dC_0. \quad (2)$$

Where Q_{j0} is the fresh water filled into the reused water tank at $N = 0(m^3/h)$, C_{m0} is the concentration of concerned pollutant in the effluent at $N = 0$ (mg/L), $d = 1 - E$, remained rate of the pollutants, $0 < d < 1$;

At $N = 1$, a part of wastewater (Q_r) with the concentration of pollutants (C_{m0}) flows into reused water tank. The concentration of pollutants in the treated wastewater is calculated as follows:

$$C_{01} = \frac{Q_r C_{m0} + Q_{j1} C_j + C_0 Q_0}{Q_0}, \quad (3)$$

$$= C_0 + \frac{Q_r C_{m0} + Q_{j1} C_j}{Q_0}, \quad (4)$$

where Q_r/Q_0 is the rate of wastewater reuse and can be presented by R; Q_{j1} is the fresh water filled into the reused water tank at $N = 1(m^3/h)$; C_{j1} is the concentration of the concerned pollutant in the fresh water, is generally ignored, because $C_{j1} \ll C_{m0}$; $C_{m0} = dC_0$, as showed in Equation (2).

The Equation (4) is simplified as:

$$C_{01} = C_0 + RdC_0. \quad (5)$$

Due to dC_0 as the concentration of remained pollutant in the reused wastewater after biological treatment, it is difficult to be further biodegraded by the same biochemical process. So the concentration of treated wastewater C_{m1} is calculated as follows:

$$C_{m1} = dC_0 + RdC_0 = dC_0(1 + R). \quad (6)$$

At $N = 2$, the processes and the conditions of the derivation are the same as those at $N = 1$,

$$C_{02} = \frac{Q_r C_{m1} + Q_{j2} C_j + C_0 Q_0}{Q_0}, \quad (7)$$

$$= C_0 + \frac{RQ_0 dC_0(1 + R) + Q_{j2} C_j}{Q_0}, \quad (8)$$

where $C_j \approx 0$, the expression of C_{02} is given by

$$C_{02} = C_0 + dC_0(R + R^2). \quad (9)$$

The same as at $N = 1$, the concentration of pollutants in the effluent, C_{m2}, at $N = 2$, is showed as following:

$$C_{m2} = dC_0 + dC_0(R + R^2), \quad (10)$$

$$= dC_0(1 + R + R^2). \quad (11)$$

Where Q_{j2} is the fresh water filled into the reuse water tank at $N = 2(m^3/h)$, C_{m2} is the concentration of concerned pollutant in the effluent at $N = 2$ (mg/L); C_{02} is the concentration of concerned pollutant in the influent at $N = 2$ (mg/L).

At $N = n$, C_{0n} and C_{mn} are assumed as following:

$$C_{0n} = C_0 + dC_0(R + R^2 + R^3 + \cdots + R^n), \quad (12)$$

$$C_{mn} = dC_0(1 + R + R^2 + R^3 + \cdots + R^n). \quad (13)$$

On the assumption Equation (13), at $N = n + 1$, a deduction equation, as $C_{mn+1} = dC_0(1 + R + R^2 + R^3 + \cdots + R^{n+1})$, must be proved. It is demonstrated as follows. Because

$$C_{0n+1} = \frac{Q_r C_{mn} + Q_{jn+1} C_j + C_0 Q_0}{Q_0}. \quad (14)$$

Where $Q_r = RQ_0$, the Equation (14) becomes as

$$C_{0n+1} = \frac{RQ_0 C_{mn} + Q_{jn+1} C_j + C_0 Q_0}{Q_0}. \quad (15)$$

According to the Equation (15), and considering $C_j \approx 0$, C_{0n+1} and C_{mn+1} are simplified as:

$$C_{0n+1} = C_0 + RdC_0(1 + R + R^2 + R^3 + \cdots + R^n) \quad (16)$$

$$C_{mn+1} = dC_0 + dC_0(R + R^2 + R^3 + \cdots + R^{n+1}) \quad (17)$$

$$= dC_0(1 + R + R^2 + R^3 + \cdots + R^{n+1}). \quad (18)$$

The Equation (18) is the same as the deduction equation of C_{mn+1}. That means that the hypothesis of Equation (12) and Equation (13) is true.

In the Equation (13), because

$$(1 + R + R^2 + R^3 + \cdots + R^n) = \frac{1 - R^{n+1}}{1 - R}, \quad (19)$$

Equation (13) is expressed as:

$$C_{mn} = dC_0 \frac{1 - R^{n+1}}{1 - R} = (1 - E) C_0 \frac{1 - R^{n+1}}{1 - R}. \quad (20)$$

The Equation (20) is a basic equation of the water quality model which gives the relationship among C_{mn}, R, E, and C_0.

2.2 Equations for C_s and R calculation

According to the water quality model in Equation (20), the equations for C_s and R calculation were derived as follows:

Based on the mass balance of the wastewater reuse system,

$$QC_s = C_{mn} Q_r + C_j Q_j. \quad (21)$$

Because $C_j \approx 0$ and on the Equation (21),

$$C_s = C_{mn} \frac{Q_r}{Q} = C_{mn} \left(\frac{Q_w + Q}{Q} \right) R, \quad (22)$$

$$C_s = C_0(1 - E) \frac{1 - R^{n+1}}{1 - R} \left(1 + \frac{Q_w}{Q} \right) R. \quad (23)$$

The Equation (23) expresses the concentration of pollutant in the reused wastewater at $N = n$.

From Equation (20) and Equation (23), when $R < 1$, and $n \to \infty$, equations of C_{mn}, C_s, and R are simplified as

$$C_{mn} = C_0 \frac{1 - E}{1 - R}, \quad (24)$$

$$C_s = \frac{C_0(1 - E)(1 + Q_w/Q) R}{1 - R}, \quad (25)$$

$$R = \frac{C_s}{C_0(1 - E)(1 + Q_w/Q) + C_s} \times 100\%, \quad (26)$$

where $1/(1 - R)$ is the concentrated factor of the pollutant in the reused wastewater, directly related to the reuse rate of the treated wastewater. If the reuse rate $R > 0$, the factor $1/(1 - R) > 1$.

The Equation (25) is the water quality model of wastewater reuse system that is hoped to make in this study. The Equation (26) is a function to determine the reuse rate of the treated wastewater which is derived from the water quality model of wastewater reuse system.

2.3 Verification of the model with experiment data

In the same conditions of R, E, N and C_0, a group of data of color and C_{mc}, were calculated with the Equation (20) and the conditions for C_{mc} calculating is given in Table 1. For calculation, the C_0 was taken 100 degree, the average of C_0 data, 40 and 140, at $N = 0$ in Table 1 and the R was about 0.65(or 65%). For comparing C_{mc}(calculated dada) and C_m(the experiment data) of color measured in the effluent from a MBR for toilet wastewater treatment and reuse, two curves of C_m and C_{mc} was made and shown in Fig.2.

Table 1 The conditions for comparison between C_m and C_{mc} of color

Date	N, n	C_0, mg/L	C_m, mg/L	E, %
2003/10.27	0	60	40	33
10.31	0	140	60	45
11.3	1	100	40	59
11.11	1	75	30	60
11.14	1	150	60	60
11.18	2	100	60	50
11.20	2	60	50	28
11.24	2	120	100	17
12.5	3	120	70	29
12.11	3	120	80	38
12.19	4	120	100	25
12.29	5	150	100	25
2004/3.3	9	160	120	29
3.18	11	150	100	29

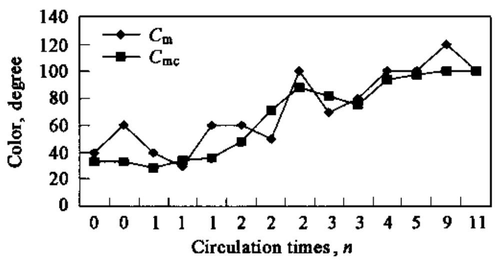

Fig.2 Comparison between C_m and C_{mc} of color in the effluent from a MBR for toilet wastewater treatment and reuse

For verification of the model, a comparison of COD between C_{mc}, calculated with the Equation (20), and C_m measured from another MBR system for toilet wastewater treatment was made. Table 2 shows the date range of all parameters and the conditions for calculation of C_{mc}. In calculation, the C_0 was taken 246 mg/L, the average of C_0 was 211 and 280 at $N = 0$ and $N = 1$. The comparison curves of C_{mc} and C_m of COD was given in Fig.3.

Table 2 The conditions for comparison between C_m and C_{mc} of COD

Date	Number	C_0, mg/L	C_m, mg/L	E, %	R, %
2004.1.7	0	211.0	140.5	33	40
2004.1.15	1	280.1	147.8	40	46
2004.2.13	6	269.1	190.5	38	27
2004.2.19	6	423.1	194.7	42	16
2004.2.26	10	433.5	163.4	58	29
2004.3.10	12	590.5	171.3	67	46
2004.3.17	13	532.0	199.7	67	55
2004.3.23	14	453.2	233.1	56	43
2004.3.24	14	413.3	234.3	46	43
2004.4.2	16	370.0	271.0	35	47
2004.4.5	16	438.8	281.8	31	46
2004.4.7	16	599.5	264.7	46	50

From Fig.2 and Fig.3, we can see that Equation (20) simulates the accumulation of color and COD in reused water

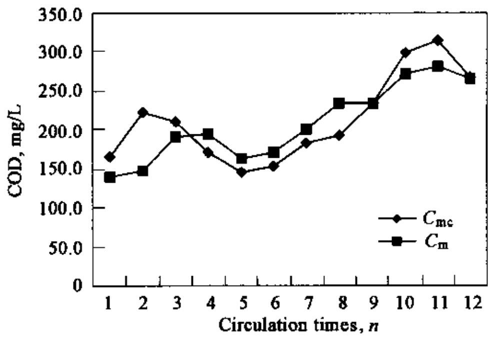

Fig.3 Comparison between C_m and C_{mc} of COD in the effluent from a MBR for toilet wastewater treatment and reuse

very well. On the other hand, the water quality model of wastewater reuse system deduced from Equation (20) is creditable.

3 Discussion and application of the model

3.1 Limit of R caused by standards for reused wastewater quality

The users of the technologies for water reuse always expect the R to be 100% (or $R = 1$), but from Equation (24) and Equation (25), if $R = 100\%$, C_{mn} and C_s will be infinite. It means that setting R at 100% will not work. And then, if $R = E$, from the same equations, the C_{mn} and the C_s will be expressed as,

$$C_{mn} = C_0, \tag{27}$$

$$C_s = C_0\left(1 + \frac{Q_w}{Q}\right)E. \tag{28}$$

Equation (27) and Equation (28) show that if $R = E$, C_{mn} will be equal to the C_0, that will also not be accepted.

Therefore, for all the parameters of the reused wastewater to meet the reuse water quality standard, the smallest R must be selected from all the calculated R on every parameter of the reused wastewater quality.

Based on the experiment results of a membrane bioreactor for toilet wastewater treatment and reuse (Xu, 2003), and the reuse water standard and quality for city wastewater reclamation and reuse(GB/T18920-2002), the R on turbidity and color was 82.9%, 37%, calculated by Equation (26) respectively, at $Q = 10$ t/d, $Q_w = 1$ t/d, and $Q_w/Q = 1/10$ (Table 3). From the experimental and calculated results, the R of turbidity is the highest, and that of color is the lowest. So, color is the control parameter to determine R for the toilet wastewater reclamation and reuse. The result showed that if all the parameters could meet water quality standards, the wastewater reuse rate would be less than 40%. The impact of R on C_s is shown in Fig.4 made with the conditions of C_0 and E in the Table 3. From the Fig.4, as R becomes higher, the quality of the reused water will become poorer.

Given the discussion above, the treated toile wastewater can not be reused at R of 100%, and R is thus recommended at less than 40%. But if E of color is improved, R can be increased higher, that can be found in Fig. 5. However, the appropriate value of R will be determined by local conditions of MBR for toilet wastewater treatment and reuse.

Table 3 *R* **needed for quality of the treated wastewater to meet the reuse water standard**

Parameters	Tubidity, NTU	Color, degree
C_0	187	150
C_s	0.5	30
Standards	5	30
E, %	99.5	70
R, %	82.9	37

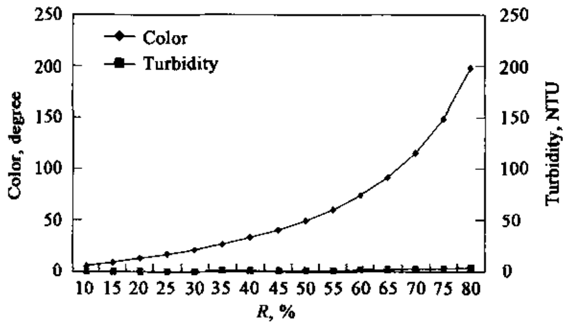

Fig.4 Relation between R and C_s (on color and turbidity)

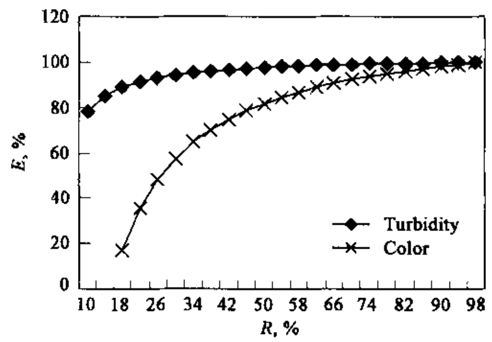

Fig.5 Relation between R and E

3.2 Impact of E on R, and application of the model

The relationship between E and R is given in Fig.5. It is obvious that R is rising along with E. So, the improvement of pollutant removal is an essential way to increase R. From Fig. 5, we can see that if E of color improved from 70% to 96%, R can be enhanced from 40% to 90% (or R from 0.40 to 0.90).

According to the results, it is very important to study and develop the cost-effective and safe technologies for improving the removal of color of toilet wastewater treatment and reuse process.

4 Conclusions

Circulation concentration problem exists in the wastewater treatment and reuse processes because the removal efficiency of pollutant is generally less than 100%. A water quality model was thus made with mathematics induction in order to calculate the accumulated concentration of pollutants in the treated wastewater.

Based on the model, the equations to calculate C_s, the quality of reused wastewater, and R, reuse rate of treated wastewater were derived as,

$$C_s = C_0 \frac{1-E}{1-R}\left(1+\frac{Q_w}{Q}\right)R,$$

$$R = \frac{C_s}{C_0(1-E)(1+Q_w/Q)+C_s} \times 100\% .$$

Color is the limit factor for wastewater reuse, and with E of color at 70%, the reuse rate of treated wastewater would be less than 40%, when all pollutants of treated wastewater meet with the standard of reuse water quality in toilet wastewater treatment and reuse. But if E of color is improved from 70% to 96%, R can be enhanced from 40% to 90%.

In toilet wastewater treatment and reuse, the improvement of color removal is an essential and important way to increase wastewater reuse rate.

Nomenclatures:

BOD_5: biochemical oxygen demand, mg/L;
COD: chemical oxygen demand, mg/L;
C_j: concentration of the concerned pollutant in fresh water, mg/L;
C_m: concentration of the concerned pollutant in effluent water, mg/L;
C_0: concentration of the concerned pollutant in influent, mg/L;
C_s: concentration of the concerned pollutant in reuse water, mg/L;
E: removal efficiency of pollutant in wastewater(< 1 or 100%);
HRT: hydraulic retention time, h;
MBR: membrane bioreactor;
NH_3-N: ammonia nitrogen, mg/L;
N: circulation times of reused water in wastewater reuse syste, n;
Q_j: flow rate of fresh water replenished into used water, m^3/h;
Q: flow rate of used water, m^3/h;
Q_0: flow rate of influent to water treatment unit, m^3/h;
Q_w: flow rate of wastewater added into water reuse system, m^3/h;
Q_r: flow rate of reuse water, m^3/h;
Q_p: flow rate of discharge water, m^3/h
R: reuse rate of treated waste water(< 1 or < 100%);
SRT: sludge retention time, h.

References:

Auer M T, Niehaus S L, 1993. Modeling fecal coliform bacteria I: Field and laboratory determination of loss kinetics[J]. Water Research, 27(4): 693—701.

Fan Y B, Wang J S, 1995. Membeane bioreactor technology for the treatment of water and wastewater[J]. Chinese Journal of Environmental Science, 16 (5): 79—81.

Gu G W, He Y L, 2002. Wastewater treatment: membrane bioreactor-study and application[M]. Beijing: Chemical Industry Press. 38.

Huang X, 1998. Development of study on membrane bioreactor process for wastewater treatment[J]. Research of Environmental Sciences, 11(1): 40—44.

Saqqar M M, Pescod M B, 1992. Modeling coliform reduction in wastewater stabilization ponds[J]. Water Science and Technology, 26(7/8): 1667—1728.

Takashi A, 1998. Water quality management library volume 10: wastewater reclamation and reuse[M]. USA: Technomic Publishing Company, Inc. 705—754.

Xu H F, Fan Y B, 2002a. Development of membrane bioreactor for black water and night soil treatment[J]. Techniques and Equipment for Environmental Pollution Control, 3(6): 75—81.

Xu H F, Fan Y B, 2003. Treatment of wastewater from a toilet for reclamation with a membrane bioreactor[J]. Chinese Journal of Environmental Science, 24(2): 125—129.

Xu P, Brissaud F, Fazio A. 2002b. Non-steady-state modeling of faecal coliform removal in deep tertiary lagoons[J]. Water Research, 36(12): 3074—3082.

Yang Z Z, Sun Y J, Pang J Z, 2003. Treatment of car wastewater by conventional activated sludge membrane bioreactor[J]. Environmental Pollution and Prevention, 25(2): 104—106.

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