

Supporting Information

1 Method for the mass balance

1.1 Measurement of the carbon composition

Carbon fractions of the influent and filtrate was measured and calculated according to the methods described by Gu and Onnis-Hayden (Gu and Onnis-Hayden, 2010). The calculative Eqs. (1)–(5) and results were listed in Table S1. The COD concentration of the filtrated raw sewage by a cellulose membrane filter of 0.45 μm was defined as COD_1 . COD measurement of the supernatant was set as COD_2 after flocculated by addition of 0.6 mol/L zinc sulfate ($ZnSO_4$) at pH 10.5 and filtrated by the filter of 0.45 μm (Mamais et al., 1993). S_A was measured by a gas chromatograph (GC, 7890, Agilent, USA). BOD was measured by the rapid BOD analyzer (RB-880, Jingcheng, China).

$$S_I = 90\% COD_1 \quad (1)$$

$$S_S = COD_2 - S_I \quad (2)$$

$$S_F = S_S - S_A \quad (3)$$

$$X_s = BOD_{total} - S_S \quad (4)$$

$$X_I = COD_{tot} - S_I - S_S - X_s \quad (5)$$

1.2 Basic assumptions

1) The anaerobic-anoxic-aerobic (A/A/O) was assumed as the typical activated sludge process with nutrient removal. Due to the easily degradable characteristics, S_A and S_F flowed into the anaerobic and anoxic stage were quickly consumed by microbial metabolism, partially producing carbon dioxide (CO_2) as end product and partially being stored as biomass. Assuming acetate as organic matter (1.07 g COD/g acetate), the stoichiometric equations and related listed in the Tables S2 and S3 were used for the related biological processes.

2) The process without fine-sieving or primary sedimentation was set as a reference process with a functional unit of 10000 m^3/d . The major difference between the two processes were the amount of the X_s flowing into the biological process. As revealed by Benneouala, 20% X_s can be hydrolyzed and utilized in 5 days sludge retention time (SRT), which was adopted in the mass balance

calculation (Benneouala et al., 2017). The residual X_s was then flowing into the aerobic stage and mineralized in order to reach the effluent standard for COD concentration (50 mg/L). Here, Class 1A was set as the target discharge qualities. Deducting the concentration of inert soluble carbon fraction ($S_I = 20$ mg/L) and the required BOD concentration (10 mg/L, S_F was assumed as the carbon fraction equivalent to BOD), the effluent concentration of X_s was deduced as 20 mg/L.

1.3 Calculative process and results

1) Biomass production and aeration consumption at aerobic stage

Based on the influent and effluent concentrations of X_s at the aerobic stage, as well as the stoichiometric relationship of carbon oxidation reaction, the biomass produced can be preliminary evaluated, as listed below in the Eq. (6).

$$VSS_{\min e} = 0.4 * [X_{s_{in}} * (1 - \alpha_{re}) * (1 - \eta_{hy}) - X_{s_{en}}] \quad (6)$$

where $X_{s_{in}}$, refer to the influent concentration of X_s at the aerobic stage. For the case WWTP, it was 189 mg/L. $X_{s_{en}}$, refer to the effluent concentration of X_s . As evaluated above, it was 20 mg/L. α_{re} , refer to the entrapment efficiency of the X_s . It was 0% and 35% for the reference process and the proposed up-stage recovery process, respectively. η_{hy} , refer to the hydrolysis efficiency of X_s . As reported, only 20% of the X_s could be hydrolyzed in 5 days sludge retention time (SRT) (Benneouala et al., 2017).

Based on the stoichiometric relationship of mineralization, biomass production and oxygen consumption can be predicted. As calculated, the biomass produced was 52.5 mg VSS and 31.3 mg VSS for the reference process and the proposed up-stage recovery process, respectively. It is clear that 40.3% biomass and aeration energy can be reduced at aerobic stage.

2) Sludge production and aeration energy reduction in biological process

The calculation equation for total oxygen demand was presented below in the Eqs. (7) and (8).

$$O_T = O_c + O_{ni} - O_{de} \quad (7)$$

$$O_{ni} = 4.57 * N_{ni} * Q \quad (8)$$

where Q_T , refer to the total oxygen demand, mg O_2 /d; Q_c , refer to the oxygen consumed in carbon oxidation, mg O_2 /d; Q_{ni} , refer to the oxygen demand for nitrification, mg O_2 /d; Q_{de} , refer to the oxygen released in denitrification process, mg O_2 /d, with -2.86 mg O_2 /mg N. N_{ni} , refer to the nitrate production, mg/L; 4.57 mg O_2 /mg $NH_4^+ - N$ nitrified to $NO_3 - N$ is a constant; Q , refer to the inflow rate, m³/d. Q_c can be determined by the X_s consumed at aerobic stage by the

stoichiometric coefficient of 0.51 g O₂/g COD removed. Q_{ni} and Q_{de} were related with the sludge production and nitrogen mass balance, as revealed in the following Eqs. (9) and (10).

$$N_{ni} = N_{in} - N_{en} - N_{slu} \quad (9)$$

$$N_{slu} = 0.124 * f * W_{slu} \quad (10)$$

where N_{in} and N_{en} , refer to the influent and effluent Kjeldahl nitrogen, respectively, mg/L. N_{slu} , refer to the nitrogen content in sludge, with a conversion coefficient of 0.124 g N/g VSS, mg/L. W_{slu} , refer to the sludge produced in the biological process, kg VSS/d. It can be evaluated by the following Eqs. (11)–(15).

$$W_{slu} = W_1 - W_2 + W_3 \quad (11)$$

$$W_1 = Y * Q * (C_{in} - C_{en}) \quad (12)$$

$$W_2 = K_d * V * X_v \quad (13)$$

$$X_v = f * X \quad (14)$$

$$W_3 = f * Q * (SS_{in} - SS_{en}) \quad (15)$$

where W_1 , W_2 , W_3 refer to the biomass generated by microbial metabolism, biomass lost by endogenous metabolism, inert and particulate solids, respectively, kg VSS/d. Y is sludge yield coefficient. C_{in} and C_{en} refer to the COD inflow and outflow of the biological process, mg/L (Table S1). SS_{in} and SS_{en} are the concentration of suspended solids in and out of the biological process. As revealed by the POM recovery results, 46% of the SS was removed, compared with 0% removal for the reference process. Thus the value of SS_{in} was 116 mg/L and 215 mg/L for the up-stage process and the reference process, respectively. As for SS_{en} , 10 mg/L was assumed with Class 1A standard. The other related parameters were presented in Table S4. V is the bioreactor volume, m³. It can be calculated by the following Eq. (16).

$$V = \frac{Q * (C_{in} - C_{en})}{N * X} \quad (16)$$

3) Calculation base for aeration power

Aeration power was evaluated by data of surface aerator used. The actual oxygen requirement (AOR) was converted to standard oxygen requirement (SOR) by the following Eq. (17).

$$SOR = \frac{AOR * C_s}{\alpha * (\beta * \rho * C_{s(20)} - C_L) * 1.02^{T-20}} \quad (17)$$

where C_s referred to the oxygen saturation with 20°C, 9.07 mg/L; α is the ratio of the oxygen transfer rate in wastewater to fresh water, with value of 0.85; β is the ratio of oxygen saturation in wastewater to fresh water, with value of 0.95; ρ is the ratio of local atmospheric pressure to standard atmospheric pressure, with value of 0.97 (the average atmospheric pressure in Taiyuan City (China) is 98 kPa); C_L is the oxygen concentration in the aerobic zone, with value of 2 mg/L. T is the actual temperature, Assuming that the power efficiency of the surface aerator was 1.85 kg O₂/ kWh, the required total power in the reference process and the proposed process was evaluated.

2 Supporting tables (Tables S1–S5)

Table S1 Carbon fractions in the influent, filtrate and effluent sewage

Carbon fractions	Influent (mg COD /L)	Filtrate (mg COD /L)	Effluent ^{a)} (mg COD /L)
S_A	13.7	13.7	0.0
S_F	63.0	63.0	10.0
S_I	21.4	21.4	21.4
X_s	189.0	21.4	20.0
X_I	63.0	41.0	0

Notes: a) the carbon fractions in the effluent was deduced from the target discharge qualities of COD (50 mg/L) and the fate of the S_I (21.4 mg/L) in the effluent. S_F and X_s were assumed to be 10 mg/L and 20 mg/L, respectively.

Table S2 Stoichiometric reactions of biological functional unit in CAS system (Metcalf and Eddy, 2003)

Biological-functional unit	Stoichiometric reactions
Carbon oxidation	$5\text{CH}_3\text{COO}^- + \text{NH}_4^+ + 5\text{O}_2 \rightarrow \text{C}_5\text{H}_7\text{O}_2\text{N} + 4\text{H}_2\text{O} + 5\text{CO}_2 + 4\text{OH}^-$
Nitrification	$\text{NH}_4^+ + 1.89\text{O}_2 + 0.08\text{CO}_2 \rightarrow 0.016\text{C}_5\text{H}_7\text{O}_2\text{N} + 0.95\text{H}_2\text{O} + 0.98\text{NO}_3^- + 1.98\text{H}^+$
Denitrification	$12.5\text{CH}_3\text{COO}^- + 14.38\text{NO}_3^- + 14.38\text{H}^+ \rightarrow 1.22\text{C}_5\text{H}_7\text{O}_2\text{N} + 6.58\text{N}_2 + 12.5\text{OH}^- + 18.9\text{CO}_2 + 15.42\text{H}_2\text{O}$
Phosphorus Removal	$5\text{CH}_3\text{COO}^- + \text{NH}_4^+ + 0.1\text{H}_2\text{PO}_4^- + 4.875\text{O}_2 \rightarrow \text{C}_5\text{H}_7\text{O}_2\text{N} + 5\text{CO}_2 + 4.05\text{H}_2\text{O} + 4.1\text{OH}^-$

Table S3 Stoichiometric relationship for mass flows of biological functional unit in CAS system (Metcalf and Eddy, 2003)

Biological functional unit	COD consumption	CO ₂ emission	Biomass production
Carbon oxidation	–	0.70 g CO ₂ /g COD _{removed}	0.40 g VSS/g COD _{removed}
Nitrification	–	–0.25 g CO ₂ /g NH ₄ ⁺ -N _{removed}	0.16 g VSS/g NH ₄ ⁺ -N _{removed}
Denitrification	3.92 g COD/g NO ₃ ⁻ -N	0.70 g CO ₂ /g COD _{removed}	0.30 g VSS/g COD _{used}
Phosphorus Removal	9.06 g COD/g P _{removed}	0.70 g CO ₂ /g COD _{removed}	0.37 g VSS/g COD _{used}

Table S4 Key design parameters used for carbon mass balance evaluation

Parameters		Value	Unit
N	Sludge load	0.14	kg BOD/(kg MLSS·d)
X _R	Return sludge concentration	8000	mg MLSS /L
R	Sludge return ratio	50	%
X	Mixed liquor suspended solids	4000	mg MLSS /L
r	Inner circulation ratio	100	%
Y	Sludge yield coefficient	0.65	kg VSS/kg BOD ₅
K _d	Decay coefficient	0.05	
f	Volatile suspended solids ratio	0.75	kg VS/kg TS

Table S5 Genera (relative abundance > 1% in at least one samples)

Genus	R-POM	WAS
<i>Ottowia</i>	7.42	6.46
<i>Paraclostridium</i>	6.97	0.64
<i>Ferruginibacter</i>	0.76	4.30
<i>Saccharimonadales_norank</i>	3.61	3.80
<i>A4b_norank</i>	0.27	3.89
<i>Gemmataceae_uncultured</i>	2.92	0.50
<i>SBR1031_norank</i>	1.41	3.86
<i>Psychrobacter</i>	2.58	0.00
<i>Gemmatimonadaceae_uncultured</i>	0.00	3.80
<i>Xanthobacteraceae_uncultured</i>	2.24	0.45
<i>Proteiniclasticum</i>	2.05	0.81
<i>Saprospiraceae_uncultured</i>	0.60	3.21
<i>Christensenellaceae R-7 group</i>	2.00	0.62

<i>OLB14_norank</i>	1.55	3.08
<i>DS-100_norank</i>	1.94	1.63
<i>Ardenticatenales_norank</i>	1.06	2.47
<i>SH-PL14</i>	1.93	0.05
<i>Terrimonas</i>	0.09	2.35
<i>Romboutsia</i>	0.44	2.14
<i>Acinetobacter</i>	1.90	0.04
<i>Rhizobiales Incertae Sedis_uncultured</i>	1.86	0.84
<i>Thermomonas</i>	1.21	2.07
<i>Anaerolineaceae_uncultured</i>	1.84	1.46
<i>SC-I-84_norank</i>	0.26	1.82
<i>Planctomycetales_norank</i>	1.81	0.24
<i>SJA-28_norank</i>	1.08	1.77
<i>Trichococcus</i>	1.79	0.50
<i>Rhodanobacteraceae_uncultured</i>	1.78	1.21
<i>Ellin6067</i>	0.06	1.74
<i>BD1-7 clade</i>	0.03	1.72
<i>Pirellula</i>	1.66	1.13
<i>Fimbriimonadaceae_norank</i>	1.44	0.29
<i>Phaeodactylibacter</i>	0.40	1.29
<i>CL500-29 marine group</i>	1.12	1.27
<i>Lautropia</i>	0.49	1.25
<i>Steroidobacteraceae_uncultured</i>	1.35	0.18
<i>Rhodobacter</i>	1.35	0.13
<i>Beijerinckiaceae_uncultured</i>	1.34	0.16
<i>Microtrichaceae_uncultured</i>	1.24	0.38
<i>NS9 marine group_norank</i>	0.00	1.13
<i>Nitrosomonas</i>	0.00	1.12
<i>Synergistaceae_uncultured</i>	1.19	0.14
<i>I-20_norank</i>	0.62	1.11
<i>OLB13</i>	0.00	1.06
<i>Subgroup 6_norank</i>	0.00	0.99
<i>Hyphomicrobium</i>	1.08	0.72
<i>A0839_norank</i>	1.06	0.51

3 Supporting figures

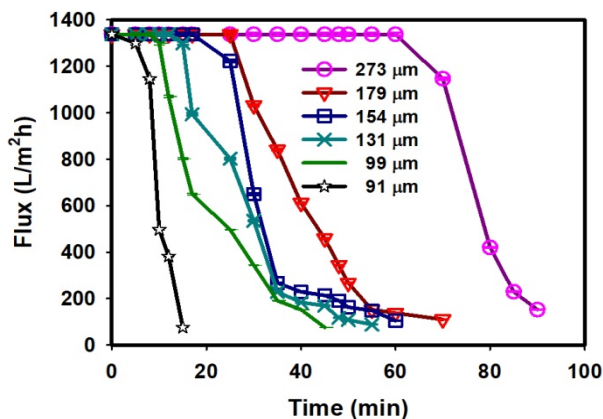


Fig. S1 Time-course profiles of flux in POM recovery by sieves with different pore sizes

References

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