

# **Overcoming barriers to net-zero emissions in wastewater treatment: Insights from a comparative analysis**

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Table S1. Wastewater characteristics of the studied WWTPs.

WWTP/ discharge standard	PE	Treatment capacity (m <sup>3</sup> /day)	Influent (mg/L)					Effluent (mg/L)					BOD:COD ratio	BOD:N ratio	BOD:P ratio	remark
			COD	BOD <sub>5</sub>	NH <sub>3</sub> -N	TN	TP	COD	BOD <sub>5</sub>	NH <sub>3</sub> -N	TN	TP				
A	1,319,000	558,232	314	138	26	29	4	18	5	0.3	9	0.14	0.44	4.8	35	
B	935,600	354,096	194	115	16	28	3	15	1	0.2	6	0.06	0.60	4.2	42	
C	2,350,000	822,276	294	174	20	33	4	15	1	0.2	7	0.05	0.59	5.2	43	
D	262,500	84,000	232	88	25	34	3	18	2	0.1	8	0.10	0.38	2.6	25	
Class IA	-	-	-	-	-	-	-	50	10	5(8)**	15	0.5	-	-	-	
E	2,415,000	502,000	351	147	35	45	5	16	2	0.3	11	0.16	0.42	3.2	31	20% industrial wastewater
F*	2,400,000	806,849	409	185	29	43	4	18	2	0.2	12	0.09	0.45	4.3	44	50% industrial wastewater
Class B	-	-	-	-	-	-	-	30	6	1.5(2.5)***	15	0.3	-	-	-	

\* Some of the wastewater characteristic of plant F in the study year was missing, and it was calculated based on average wastewater characteristic in another year. \*\* The value outside the bracket is the control indicators when the water temperature is > 12°C, and the values in bracket is control indicators when the water temperature is ≤12°C. \*\*\* From December 1 to March 31, the discharge limits in bracket will be implemented.

Effluent of plants A, B, C, and D is subject to the mandatory requirements of national standard Class IA, and effluent of the plants E and F is subject to local standard Class B.

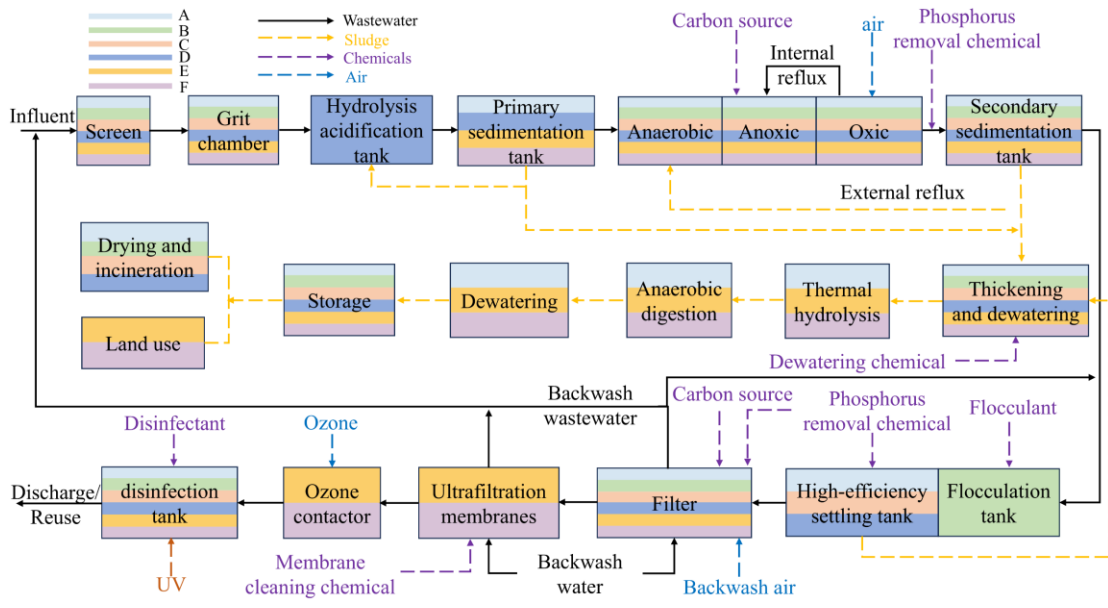


Figure S1. Flowcharts of the studied WWTPs.

Table S2. Data input into CFCT.

Category	Parameter	Unit
Influent and Effluent	Flow rate	m <sup>3</sup> /h
	Pollutant indicators (COD、BOD <sub>5</sub> 、TN、TP)	ton/year
Chemicals	Amount of each chemical used in the wastewater and sludge treatment processes	ton/year
Energy	Electricity consumption/Purchased electricity	MWh/year
	Electricity produced by solar energy/natural gas	MWh/year
	Heat consumption/Purchased heat	MWh/year
	Heat produced by natural gas	MWh/year
Transports	Distance between sludge treatment and disposal site and WWTPs	km
	Times of sludge transports	times/year
	Distance between chemical suppliers and WWTPs	km
	Times of chemical transports	times/year
	Load capacity of delivery trucks	ton
Biogas	Produced biogas	Nm <sup>3</sup>
	Methane content in biogas	%
	Biogas used in torch/gas engine/gas boiler	Nm <sup>3</sup>
Sludge	Amount of waste sludge produced	ton/year
	TS of waste sludge	%
	Amount of dried sludge produced	ton/year
	TS of dried sludge	%
	Amount of waste sludge farmland	ton/year
	Amount of waste sludge incineration	ton/year
	Sludge storage time	day
	N, P, K, C content in the sludge before storage	kg/ton TS
Reclaimed water	Amount of reclaimed water	ton/year

Table S3. Changes in emission factors.

Category	Parameter	Unit	Before optimization	After optimization	Reference
GWP	CH <sub>4</sub> GWP	kg CO <sub>2e</sub> /kg CH <sub>4</sub>	34	28	(IPCC, 2014)
	N <sub>2</sub> O GWP	kg CO <sub>2e</sub> /kg N <sub>2</sub> O	298	265	
Chemicals Production	Polyaluminium chloride (PAC)	kg CO <sub>2e</sub> /ton	110	6,190 (Calculated by mass of Al <sup>3+</sup> )	(China Urban Water Association, 2023)
	Polyacrylamide (PAM)	kg CO <sub>2e</sub> /ton	805	2,850 (Solids content>90%)	
	Aluminum sulfate [Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> ]	kg CO <sub>2e</sub> /ton	/	150 (Liquid, Al <sub>2</sub> O <sub>3</sub> 8.25% wt)	
	Ferric chloride (FeCl <sub>3</sub> )	kg CO <sub>2e</sub> /ton	/	2,860 (Calculated by mass of Fe <sup>3+</sup> )	
	Ferrous chloride (FeCl <sub>2</sub> )	kg CO <sub>2e</sub> /ton	/	220	
	Ferric oxide (Fe <sub>2</sub> O <sub>3</sub> )	kg CO <sub>2e</sub> /ton	/	Not available, refer to ferric chloride (FeCl <sub>3</sub> )	
	Citric acid	kg CO <sub>2e</sub> /ton	/	8,170	
	Sodium chlorate (NaClO <sub>3</sub> )	kg CO <sub>2e</sub> /ton	/	5,110 (Solids content>99%)	
	Hydrochloric acid (HCl)	kg CO <sub>2e</sub> /ton	/	1,200 (Concentration 30%)	
	Acetic acid (CH <sub>3</sub> COOH)	kg CO <sub>2e</sub> /ton	1,750	1,920 (Content 98%)	
	Sodium hypochlorite (NaClO)	kg CO <sub>2e</sub> /ton	/	2,990 (15% solution)	
	Methanol (CH <sub>3</sub> OH)	kg CO <sub>2e</sub> /ton	744	650 (Methanol from natural gas, liquid, content ≥ 99%) 2,960 (Methanol from coal, liquid, content ≥ 99%)	
	Sodium acetate (CH <sub>3</sub> COONa)	kg CO <sub>2e</sub> /ton	/	2,900 (Solids content>99%)	
	Liquid oxygen	kg CO <sub>2e</sub> /ton	/	1,150	
Sodium bisulfite (NaHSO <sub>3</sub> )	kg CO <sub>2e</sub> /ton	/	1,416		

	Sodium hydroxide (NaOH)	kg CO <sub>2e</sub> /ton	1,096	1,120 (50% in H <sub>2</sub> O)	(China Association of Environmental Protection Industry, 2022)
Electricity production	Average	ton/GWh	415	583.4	(Ministry of Ecology and Environment of the People's Republic of China, 2024)
				568.8	
				683	(Cai et al., 2023)
Heat production	CO <sub>2e</sub> local	ton/GWh	0	396	(Beijing Municipal Administration for Market Regulation, 2020)
Emissions from sludge handling	Incineration	kg CH <sub>4</sub> /kg dried waste	0	0.0056	(IPCC, 2019)
Reclaimed water reuse offsets	Tap water production	kg CO <sub>2e</sub> /m <sup>3</sup>	/	0.254	(Zhang et al., 2024)
			/	0.1463	(Li et al., 2023)

Table S4. Correction to the calculation formula and the reasons.

Category	Parameter	Before correction	After correction	Reasons for correction
Transports	Chemicals	'Input chemicals'!F62/10*'Emission factors'!C138*'Emission factors'!C142/1,000	'Input chemicals'!F62/10*'Emission factors'!C142/1,000	'Emission factors'!C142 is the transport EF calculated based on 'Emission factors'!C138. The formula before correction repeated the multiplication of 'Emission factors'!C138.
	N <sub>2</sub> O emissions	'Emission factors'!C200*'GWP and constants'!B11*(Input sludge and waste'!B6*'Input sludge and waste'!B7)*'Input sludge and waste'!B36/1,000+'Emission factors'!C200*'GWP and constants'!B11*'Input sludge and waste'!B11*'Input sludge and waste'!B37/1,000	'Emission factors'!C200*'GWP and constants'!B11*(Input sludge and waste'!B6*'Input sludge and waste'!B7)*'Input sludge and waste'!B36/1,000+'Emission factors'!C200*'GWP and constants'!B11*'Input sludge and waste'!B11*'Input sludge and waste'!B37/1,000*'Input sludge and waste'!E11	The original formula for calculating the CF of incineration after drying does not multiply the total solids content in the dried sludge, and should match the formula for calculating the CF of incineration after dewatering.
Incineration of sludge	CH <sub>4</sub> emissions	'Emission factors'!C201*'GWP and constants'!B8*(Input sludge and waste'!B6*'Input sludge and waste'!B7)*'Input sludge and waste'!B36+'Emission factors'!C201*'GWP and constants'!B11*'Input sludge and waste'!B11*'Input sludge and waste'!B37/1,000	'Emission factors'!C201*'GWP and constants'!B8*(Input sludge and waste'!B6*'Input sludge and waste'!B7)*'Input sludge and waste'!B36+'Emission factors'!C201*'GWP and constants'!B8*'Input sludge and waste'!B11*'Input sludge and waste'!B37*'Input sludge and waste'!E11	Incorrect application of the GWP of N <sub>2</sub> O in calculating CH <sub>4</sub> emissions. The original formula for calculating the CF of incineration after drying does not multiply the total solids content in the dried sludge, and should match the formula for calculating the CF of incineration after dewatering. There was an error in unit conversion when calculating the CF of incineration after drying.
	Electricity production from sludge incineration	-('Input sludge and waste'!B8*'Input sludge and waste'!B36*'Emission factors'!C111*'Emission factors'!C115/'GWP and constants'!B18*'Input sludge and waste'!E36)-('Input sludge and waste'!B11*'Input sludge and waste'!E11*'Input sludge and waste'!B37*'Emission factors'!C111*'Emission factors'!C116/'GWP and	-('Input sludge and waste'!B8*'Input sludge and waste'!B36*'Emission factors'!C111*'Emission factors'!C115/'GWP and constants'!B18*'Input sludge and waste'!E36)+('Input sludge and waste'!B11*'Input sludge and waste'!E11*'Input sludge and waste'!B37*'Emission factors'!C111*'Emission factors'!C116/'GWP and	Incorrect negative sign position leads to inaccurate results.

	$\frac{\text{constants!B18*Input sludge and waste!E37}}{1000000} * (\text{Emission factors!C5*Detailed results!F4+ Emission factors!C6*Detailed results!F5+ Emission factors!C7*Detailed results!F6+ Emission factors!C8*Detailed results!F7+ Emission factors!C9*Detailed results!F8})$	$\frac{\text{constants!B18*Input sludge and waste!E37}}{1000000} * (\text{Emission factors!C5*Detailed results!F4+ Emission factors!C6*Detailed results!F5+ Emission factors!C7*Detailed results!F6+ Emission factors!C8*Detailed results!F7+ Emission factors!C9*Detailed results!F8})$	
Heat production from sludge incineration	$-\left(\frac{\text{Input sludge and waste!B8*Input sludge and waste!B36*Emission factors!C112*Emission factors!C115/GWP and constants!B18*Input sludge and waste!E36}}{1,000,000} - \left(\frac{\text{Input sludge and waste!B11*Input sludge and waste!E11*Input sludge and waste!B37*Emission factors!C111*Emission factors!C116/GWP and constants!B18*Emission factors!C18/1,000,000*Input sludge and waste!E37}}{1,000,000}\right) * \text{IF}(\text{Input energy!C21}=1, \text{Emission factors!C17, Emission factors!C18})\right)$	$-\left(\frac{\text{Input sludge and waste!B8*Input sludge and waste!B36*Emission factors!C112*Emission factors!C115/GWP and constants!B18*Input sludge and waste!E36}}{1,000,000} + \left(\frac{\text{Input sludge and waste!B11*Input sludge and waste!E11*Input sludge and waste!B37*Emission factors!C111*Emission factors!C116/GWP and constants!B18*Input sludge and waste!E37}}{1,000,000}\right) * \text{IF}(\text{Input energy!C21}=1, \text{Emission factors!C17, Emission factors!C18})\right)$	Incorrect negative sign position leads to inaccurate results. When calculating the heat production by incineration of dried sludge, it was repeatedly multiplied by Emission factors!C18 and divided by 1,000,000.
Incineration of sludge	$\frac{\text{Emission factors!C108/1,000,000} * (\text{Input sludge and waste!B11*Input sludge and waste!E11*Input sludge and waste!B37*Input sludge and waste!E37}) + (\text{Input sludge and waste!B8*Input sludge and waste!B36*Input sludge and waste!E36}) * (\text{Emission factors!C5*Detailed results!F4+ Emission factors!C6*Detailed results!F5+ Emission factors!C7*Detailed results!F6+ Emission factors!C8*Detailed results!F7+ Emission factors!C9*Detailed results!F8})}{1,000,000}$	$\frac{\text{Emission factors!C108/1,000,000} * (\text{Input sludge and waste!B11*Input sludge and waste!E11*Input sludge and waste!B37*Input sludge and waste!E37}) + (\text{Input sludge and waste!B8*Input sludge and waste!B36*Input sludge and waste!E36}) * (\text{Emission factors!C5*Detailed results!F4+ Emission factors!C6*Detailed results!F5+ Emission factors!C7*Detailed results!F6+ Emission factors!C8*Detailed results!F7+ Emission factors!C9*Detailed results!F8})}{1,000,000} + (\text{Input sludge and waste!B11*Input sludge and waste!E11*Input sludge and waste!B37*Input sludge and waste!E37}) * (\text{Emission factors!C5*Detailed results!F4+ Emission factors!C6*Detailed results!F5+ Emission factors!C7*Detailed results!F6+ Emission factors!C8*Detailed results!F7+ Emission factors!C9*Detailed results!F8})$	
Energy use sludge incineration	$\frac{\text{Emission factors!C107/1,000,000} * (\text{Input sludge and waste!B11*Input sludge and waste!E11*Input sludge and waste!B37*Input sludge and waste!E37}) * (\text{Emission factors!C5*Detailed results!F4+ Emission factors!C6*Detailed results!F5+ Emission factors!C7*Detailed results!F6+ Emission factors!C8*Detailed results!F7+ Emission factors!C9*Detailed results!F8})}{1,000,000}$	$\frac{\text{Emission factors!C107/1,000,000} * (\text{Input sludge and waste!B11*Input sludge and waste!E11*Input sludge and waste!B37*Input sludge and waste!E37}) * (\text{Emission factors!C5*Detailed results!F4+ Emission factors!C6*Detailed results!F5+ Emission factors!C7*Detailed results!F6+ Emission factors!C8*Detailed results!F7+ Emission factors!C9*Detailed results!F8})}{1,000,000}$	The revised formula takes the energy consumption of sludge drying into account.

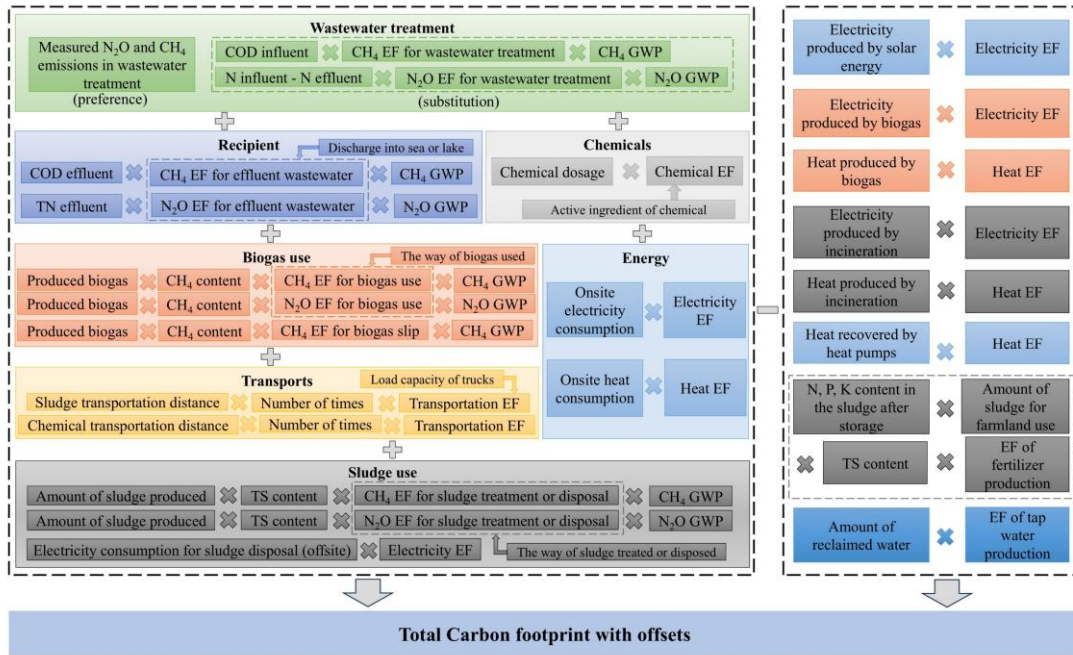


Figure S2. Flow diagram of CFCT.

Table S5. EFs applied in uncertainty analysis.

Category	Emission factor	Unit	Reference
Direct N <sub>2</sub> O emission in wastewater treatment process	0.0157	kg N <sub>2</sub> O/kg N <sub>denitrified</sub>	(Foley et al., 2008)
	0.009	kg N <sub>2</sub> O-N/kg N <sub>influent</sub>	(IPCC, 2019; China Urban Water Association, 2022)
	0.0106	kg N <sub>2</sub> O-N/kg N <sub>influent</sub>	(China Urban Water Association, 2022)
	0.00466	kg N <sub>2</sub> O-N/kg N <sub>influent</sub>	(China Urban Water Association, 2022)
	0.0081	kg N <sub>2</sub> O/kg N <sub>removed</sub>	(Li et al., 2024)
	0.00531	kg N <sub>2</sub> O/kg N <sub>influent</sub>	(Aliya et al., 2024)
Direct CH <sub>4</sub> emission in wastewater treatment process	0.0025	kg CH <sub>4</sub> /kg COD <sub>influent</sub>	(Gustavsson and Tumlin, 2013)
	0.0121	kg CH <sub>4</sub> /kg BOD <sub>influent</sub>	(IPCC, 2006; China Urban Water Association, 2022)
	0.0036	kg CH <sub>4</sub> /kg BOD <sub>influent</sub>	(China Urban Water Association, 2022)
	0.01419	kg CH <sub>4</sub> /kg BOD <sub>influent</sub>	(China Urban Water Association, 2022)
	0.0091	kg CH <sub>4</sub> /kg COD <sub>removed</sub>	(Li et al., 2024)
	0.00575	kg CH <sub>4</sub> /kg COD <sub>removed</sub>	(China Urban Water Association, 2023)

Table S6. Comparison of  $CF_p$  and  $CF_v$  of WWTPs in different countries.

Country/ Region	WWTP	$CF_p$ (kg CO <sub>2</sub> - eq/PE/year)	Average $CF_p$ (kg CO <sub>2</sub> - eq/PE/year)	$CF_v$ (kg CO <sub>2</sub> -eq/m <sup>3</sup> )	Average $CF_v$ (kg CO <sub>2</sub> -eq/m <sup>3</sup> )	Reference
China	A	58	58	0.4	0.5	This study
	B	55		0.4		
	C	61		0.5		
	D	71		0.6		
	E	52		0.7		
	F	52		0.4		
Poland	P1	20	31	0.6	0.7	(Maktabifard et al., 2022)
	P2	38		0.7		
	P3	18		0.7		
	P4	36		0.6		
	P5	43		0.8		
Finland	F1	72	63	0.7	0.7	
	F2	44		0.6		
	F3	57		0.6		
	F4	77		0.7		
South Korea	K	56	/	0.3	/	(Shahid and Choi, 2023)
Scandinavia	16 WWTPs	7-108	46	/	/	(Gustavsson and Tumlin, 2013)

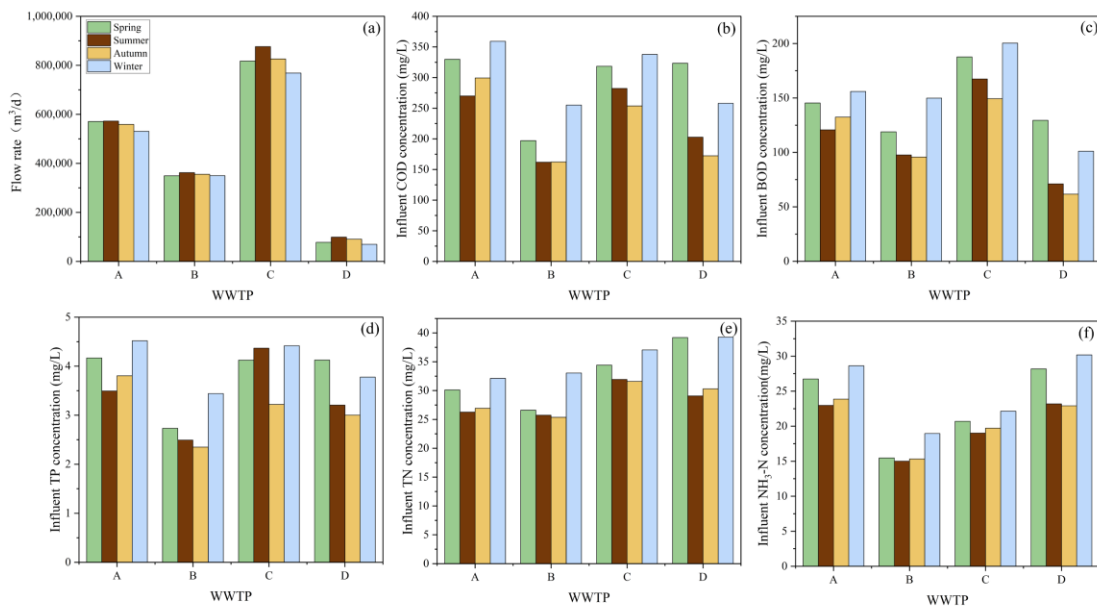


Figure S3. Seasonal wastewater characteristics of four WWTPs in southern China: (a) flow rate; (b) influent COD concentration; (c) influent BOD concentration; (d) influent TP concentration; (e) influent TN concentration; (f) influent NH<sub>3</sub>-N concentration.

Table S7. Comparison of average energy consumption of WWTPs in different countries.

Location	Energy consumption			Reference	
	kWh/m <sup>3</sup>	kWh/kg BOD removed	kWh/kg TN removed		
Poland	0.21	0.33	2.81	18.75	(Maktabifard et al., 2022)
Finland	0.53	1.98	16.82	70.37	(Shahid and Choi, 2023)
Korea	0.30	1.99	9.44	77.87	This study
China	0.36	2.69	13.34	94.93	

Note: This energy consumption data is the average of the wastewater treatment plants studied and does not represent the national average.

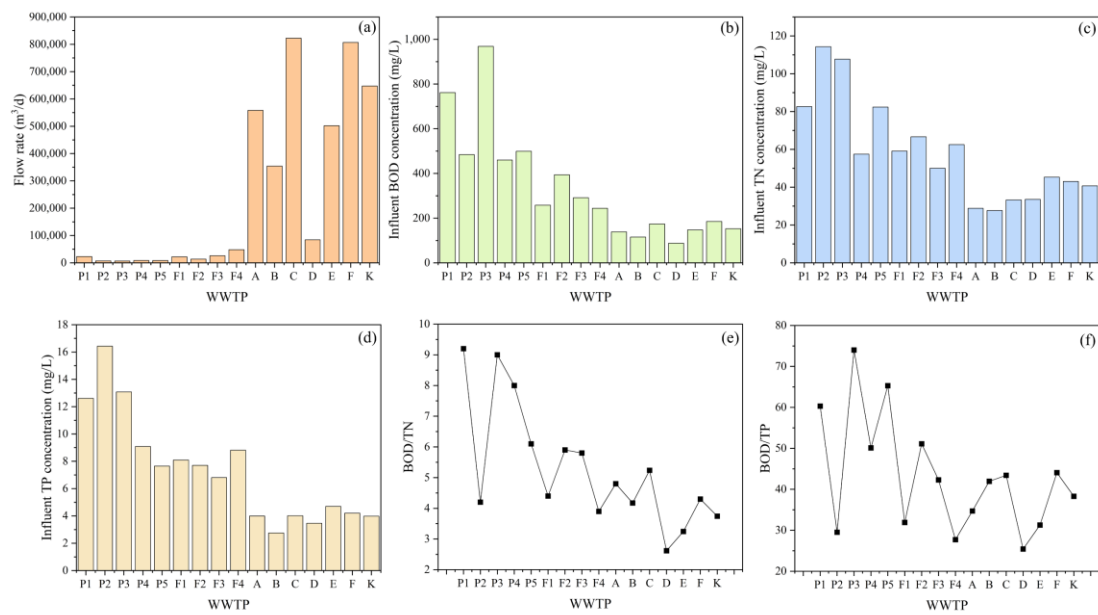


Figure S4. Wastewater characteristics of the studied Chinese WWTPs, typical Polish plants and Finnish plants (P1-P5 are located in Poland, F1-F4 represent Finnish WWTPs, and A-F are Chinese plants studied, K denotes Korean facility).

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