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A novel index of total oxygen demand for the comprehensive evaluation of energy consumption for urban wastewater treatment

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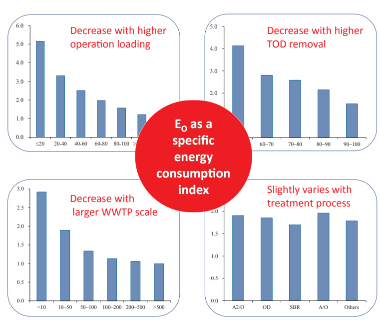
HIGHLIGHTS

- Total oxygen demand (TOD) is proposed for characterizing oxygen-consuming pollutants.
- TOD accounts for the mass of oxygen for both organics decomposition and nitrification.
- Energy consumption efficiency of WWTPs is evaluated by E_O, the unit mass TOD removal.
- Operation data from 2022 WWTPs in China are analyzed using the novel E_O index.
- Ammonia nitrification contributes almost half of the TOD based on WWTPs data in China.

GRAPHICAL ABSTRACT



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ABSTRACT

In wastewater treatment plants (WWTPs), the majority of energy inputs is consumed by aeration systems to support both the biochemical oxidation of organics and transformation of ammonia-nitrogen into nitrate-nitrogen. Consequently, WWTPs energy efficiency evaluation only based on metrics derived from the organic constituents such as chemical oxygen demand (COD) or biological oxygen demand (BOD) may not reflect the true energy consumption of WWTPs with variable influent quality. Therefore, to overcome this limitation, total oxygen demand (TOD) is introduced in this article, and a novel index E_O, namely the energy consumption for the removal of a unit mass of TOD is proposed for evaluating the energy efficiency in WWTPs. Furthermore, by considering the stoichiometric relations of oxygen consumption for the oxidation of both organics and ammonia-nitrogen, methods for calculating the E_O are proposed. Using the novel E_O index and the available annual operation data of 2022 WWTPs, the current status of energy consumption for wastewater treatment in China were analyzed. The findings show an average E_O decrease from 5.2 kWh/kg to 1.2 kWh/kg as the WWTP loading rates increase from 20% to 100%. Also, E_O decreased from 4.1 kWh/kg to 1.5 kWh/kg as the average TOD removal increased from 60% to over 90%. Moreover, E_O decreased from 2.9 kWh/kg to 1.0 kWh/kg as the WWTP scale increased from less than 10,000 m^3/d to over 5,00,000 m^3/d. Thus, the energy efficiency of WWTPs

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increases with increasing loading rates, TOD removal, and scale. Also, the wastewater treatment technology applied influences the E_O significantly, especially for small- and medium-size WWTPs with capacities less than 50,000 m^3/d which account for circa 76% of all WWTPs in China. The WWTPs applying sequential batch tractors (SBR) tended to show lower average E_O (< 1.7 kWh/kg) than those applying anaerobic/oxic (A/O), anaerobic/anoxic/oxic (A^2/O) and oxidation ditch (DO) (1.9 kWh/kg ≤ E_O ≤ 2.0 kWh/kg). Thus, as an index of the energy consumption per unit mass of TOD removed, E_O reflects the essence of wastewater treatment for pollutants removal in contrast to other existing energy indices based on the volume of treated wastewater. Moreover, due to the large variability of the WWTPs influent qualities, the TOD contributed by ammonia-nitrogen varied widely between 12.2% and 80.7% of the total TOD. Therefore, E_O calculation based on TOD but not merely the organic component (COD or BOD) provides a more comprehensive index for evaluating and optimizing the energy efficiency of WWTPs.

1. Introduction

Urban wastewater treatment plants (WWTPs) are energy-intensive facilities that consume significant amounts of energy [1]. For conventional WWTPs, 25% to 60% of the operating costs are associated with energy use [2,3]. Electricity is usually the main energy source, and its price varies widely from one utility to the other. It has been reported that electric power account for 15–30% of the total running costs for large WWTPs and 30–40% for smaller ones [4]. In the United States and the whole North America, electricity consumption accounts for 30–35% of the total operation and maintenance costs of WWTPs [5,6]. Conversely, in China, the percentage of costs for energy consumption in WWTPs is considerably higher than that for personnel, equipment depreciation, and chemical consumption [7], and can account for 30–60% of the total operating costs [8]. Therefore, with the increasing need to construct new WWTPs or expand old ones (an annual increase of wastewater treatment capacity of about 1×10^7 m^3/d recently), energy consumption becomes an issue drawing wide attention [9,10].

Evaluation and comparison of energy efficiency in various WWTPs often requires an energy index. The simplest index widely used in China is the energy consumption per unit volume of wastewater treated, in terms of kWh/m^3 [11]. Nonetheless, this index ignores the variability of WWTPs influent quality and pollutants removal levels [12]. Consequently, assessment of WWTPs using this index culminates in contradictory results on energy consumption [7,13,14], whereby some show a significant influence of treatment process and scale on the energy consumption per unit volume, while others show a complete contrast. With the increasing need to upgrade existing WWTPs for enhanced organics and nutrients removal to meet the increasingly stringent effluent discharge regulations or for other reclamation and reuse purposes, adoption of more advanced treatment technologies and operational schemes become common practices in China [15,16]. It is thus required that a more comprehensive index be developed to assist the rational evaluation of the energy efficiency of WWTPs not only regarding the quantitative outcome but more importantly the qualitative outcome of the energy consumed for wastewater treatment [17–19].

In a WWTP, the energy inputs (mostly in the form of electricity) are mainly consumed for two distinctive purposes, namely provision of gravity water head and/or mechanic mixing (usually by pumps/mixers), and provision of oxygenated air (also called aeration). Under given conditions, the energy consumed for pumping and mixing is mainly determined by the volume of the wastewater treated, whereas that for aeration is determined not only by water volume but also the mass of oxygen-consuming pollutants. Reports indicate that aeration accounts for 50–75% of the total WWTP energy expenditure [20,21].

From over one century ago when the activated sludge process became popular for wastewater treatment, aerobic decomposition of organics was taken as the sole objective and biological oxygen demand (BOD) was introduced as an indicator of the aggregate organic constituents in the wastewater. As the BOD measurement usually takes a long time (requires at least five days incubation), another parameter, namely chemical oxygen demand (COD) which can be analyzed relatively quickly has become an alternative indicator of the organic constituents. Nonetheless, the coexisting reductive inorganic constituents in the wastewater also consume oxygen, albeit very minimal. Consequently, electricity consumption in the biological treatment unit is often evaluated based on BOD or COD removal as kWh/kg·BOD or kWh/kg·COD [2,22]. However, such an evaluation inevitably neglects the fact that in a biological treatment unit the transformation of ammonia-nitrogen into nitrate-nitrogen (namely, nitrification), a process carried out by nitrifying bacteria, also substantially consumes oxygen. This vital process can no longer be ignored as nitrification and the subsequent denitrification become increasingly critical for WWTP effluent quality control. Therefore, both organics and ammonia-nitrogen should be considered when defining the oxygen-consuming pollutants in wastewaters.

A cue is taken from the study of natural purification in environmental waters, whereby oxygen consumption potential (OCP) has been proposed as a surrogating parameter for estimating the overall strength of oxygen-consuming pollutants [23–25]. The OCP of a receiving waterbody mainly comprises of two components, namely the primary oxygen consumption directly related to bacterial degradation of organic matter and ammonia, and secondary oxygen consumption related to the photosynthesis process where algae growth is promoted by nutrients, such as phosphorus and nitrogen [26]. In this way, both organics and nutrients in water can be characterized by a single indictor of OCP by analyzing the related oxidation processes. For the biological processes in WWTPs, the secondary oxygen consumption related to algae growth may not occur, but the primary oxygen consumption related to organics and ammonia degradation may be similar to that occurring in environmental waters. Therefore, the OCP principle can partially guide the development of a new energy index to characterize the oxygen-consuming pollutants in wastewaters.

Therefore, by integrating the traditional organics indicator (BOD or COD) into the OCP principle, a novel energy index is developed in this study based on the calculation of the total oxygen demand (TOD) which consists of the oxygen consumed both for the oxidation of organic pollutants and nitrifying ammonia-nitrogen. The organics component of TOD is characterized by an equivalent mass of oxygen consumed (the same value as BOD), while the ammonia-nitrogen component of TOD is derived from the stoichiometric relation that 4.18 g of oxygen is consumed for the complete oxidation of 1 g of ammonia-nitrogen [27]. Hence, the WWTPs energy efficiency is evaluated by the energy consumption for the removal of a unit mass of TOD. The applicability and advantages of TOD as a WWTPs energy efficiency index is highlighted through an analysis of the available data from over 2000 WWTPs covering broad geographic regions in China.

2. Materials and methods

2.1. Data collection and processing

The data were obtained from the Urban Drainage Statistical Yearbook [28] and the Environmental Protection Departments of the

People's Republic of China. All data were quality-checked before analysis to ensure their reliability. The data were then screened to select 2022 WWTPs that were running in 2014, for which there was information about the treatment process, design capacity, annual average loading rate, annual electricity consumption, biological oxygen demand (BOD_5) and ammonia-nitrogen ($NH_4{}^+$-N) concentrations in the influents and effluents. Pearson correlation analysis was carried out to evaluate the correlation between energy consumption and related factors at a level of significance of $p < 0.01$. Subsequently, the specific index of energy consumption per unit mass TOD removal was calculated. A statistical analysis was further carried out to determine the distribution of the energy consumption indicator using IBM SPSS Statistics 13.0 software (IBM Corporation, Armonk, NY, USA). Finally, the influence of treatment scale, loading rate, treatment process and TOD removal on the energy consumption of wastewater treatment were explored through multivariate statistical and classification analysis methods.

Based on the level of economic development, China was divided into four regions, namely Eastern, Northeast, Central, and Western regions (Fig. 1). The Eastern region comprised ten provinces: Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan. The Northeast region included three provinces: Liaoning, Jilin, and Heilongjiang. The Central region consisted of six provinces: Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan. The remaining provinces were classified under the Western region. The characteristics of selected WWTPs in China and corresponding to the four regions are shown in Table 1 and Fig. 1. It should be noted that energy consumption, in this study, refers to electric power consumption (kWh), which is the most common energy source used in WWTPs.

2.2. TOD calculation

It is neither practical nor necessary to calculate the energy consumed for the removal of individual pollutants (e.g. nitrogen, phosphate, heavy metals) since there are numerous kinds of pollutants in wastewater. In a conventional WWTP, aeration is an essential process and accounts for the largest fraction of plant energy costs, ranging from 55 to 70% of the plant energy consumption [3]. The function of aeration is to transfer oxygen to the mixed liquor to allow for the aerobic biodegradation and removal of pollutants. The concept of TOD was introduced for characterizing the total oxygen consuming pollutants. Thus, the energy consumption can be measured by the weight of the TOD removed. The mass of TOD removed is an equivalent mass, obtained by summing the mass of all oxygen consuming pollutant removed, each multiplied by an assigned weight. For the calculation of TOD in this study, organic matter and $NH_4{}^+$-N were considered. As demonstrated above, the calculation of TOD considers that organic matter consumes oxygen for biological decomposition, which can be directly characterized by BOD_5. Moreover, oxygen is also consumed by $NH_4{}^+$-N during nitrification. Considering the chemical formula of a microbial cytoplasm of $C_5H_7NO_2$, the complete nitrification process is represented by the following equation:

$$NH_4^+ + 1.83O_2 + 0.094CO_2 + 0.024HCO_3^- \rightarrow 0.024C_5H_7NO_2 + 1.95H^+ + 0.977NO_3^- + 0.0953H_2O \quad (1)$$

Eq. (1) shows that 1 g of $NH_4{}^+$-N consumes 4.18 g O_2. Therefore, the concentration of TOD (C_{TOD}, g/m^3) in wastewater can be calculated with Eq. (2):

$$C_{TOD} = C_{BOD_5} + 4.18 \cdot C_{NH_3} \quad (2)$$

where C_{BOD_5} and C_{NH_4} are the concentration of BOD_5 and $NH_4{}^+$-N in wastewater, respectively (g/m^3).

2.3. Specific energy consumption based on TOD removal

Based on the calculation of the concentration of TOD in wastewater,

Fig. 1. Distribution of selected WWTPs in four regions of China.

Table 1
Characteristics of selected WWTPs in China and its sub-regions.

Index		Eastern region	Northeast region	Central region	Western region	Whole country
Total design capacity (10^6 m^3/d)		67.42	10.53	20.78	8.49	107.22
Total daily energy consumption (10^6 kWh/d)		15.02	2.25	3.71	1.87	22.85
Operation loading rate[a] (%)		87.2 (2.2–200)	83.1 (3.95–140)	88.4 (4.7–188)	88.2 (18.9–151)	86.8 (2.2–200)
BOD_5[a] (mg/L)	Influent	120.5 (13.7–384)	104.9 (5.5–978)	115.1 (8.21–320)	111.0 (11–370)	109.5 (5.5–978)
	Effluent	8.65 (1.07–30)	6.55 (0.06–52)	11.0 (0.58–37)	8.47 (0.09–26.7)	8.10 (0.06–52)
$NH_4{}^+$-N[a] (mg/L)	Influent	24.5 (4.46–67.7)	24.1 (1.78–300)	28.6 (3.13–341)	28.8 (3.92–88)	25.6 (1.78–341)
	Effluent	3.53 (0.11–17)	2.17 (0.08–30.3)	5.31 (0.08–25)	3.00 (0.19–25.2)	3.19 (0.08–30.3)

[a] Mean value (min–max values in brackets).

the daily reduction of TOD in the WWTPs is determined by:

$$\Delta\ m = \frac{Q\cdot(C_{TOD,I} - C_{TOD,O})}{1000} = \frac{Q\cdot\Delta C_{BOD_5} + 4.18\cdot Q\cdot\Delta C_{NH_4}}{1000} \tag{3}$$

where Δm is the amount of TOD (kg/d) removed; Q is actual volume of wastewater treated (m^3/d); $C_{TOD,I}$ and $C_{TOD,O}$ are the average annual TOD concentrations in the influent and effluent, respectively (g/m^3); $\Delta C_{BOD_5}$and ΔC_{NH_4} are the differences in BOD_5 and $NH_4{}^+$-N concentrations in the influent and effluent, respectively (g/m^3).

The removal rate of TOD (R_O, %) of a WWTP can be calculated as the ratio between the removed load of TOD and the influent TOD load, according to the following expression:

$$R_O = \frac{C_{TOD,I} - C_{TOD,O}}{C_{TOD,I}} \times 100\% \tag{4}$$

Based on the daily reduction of TOD in the WWTPs, the energy consumption for a unit mass TOD removal (E_O, kWh/kg) is, therefore, calculated by dividing the daily electric energy consumption by the corresponding amount of TOD removed, as follows:

$$E_O = \frac{E_a}{365\cdot\Delta m} = E_d/\Delta m \tag{5}$$

where E_a is the annual electric energy consumption in a WWTP (kWh/y), E_d is the daily electric energy consumption in a WWTP (kWh/d).

For comparison, the energy consumption per volume of treated wastewater (E_V, kWh/m^3) is also calculated by dividing the daily electric energy consumption with the treated wastewater volume:

$$E_V = E_d/Q \tag{6}$$

3. Results and discussion

3.1. Energy consumption in the selected WWTPs

Table 2 shows the Pearson's correlations between energy consumption, TOD reduction, and volume of wastewater treated for 2022 WWTPs in China. All the correlations were significant ($p < 0.01$) and positive, with coefficients of 0.873 and 0.871. Overall, when compared with treated wastewater volume, the TOD reduction showed stronger correlations with energy consumption. Therefore, E_O is a more suitable index for evaluating energy consumption in WWTPs.

Characteristic values of the energy consumption of the selected WWTPs in China in 2014 are shown in Table 3. Overall, average E_O and E_V values of 1.860 kWh/kg and 0.296 kWh/m^3 were recorded, whereby 80% of the WWTPs had E_O values between 0.553 and 3.089 kWh/kg and E_V values between 0.099 and 0.465 kWh/m^3. Moreover, the variability of E_O, as indicated by the standard deviations, was larger than that of E_V. The higher deviations of the E_O related to the notable differences in wastewater quality (in terms of removed BOD_5 and $NH_4{}^+$-N), as shown in Table 1. Also, the average value of E_V was larger than that of 0.290 kWh/m^3 reported for 559 WWTPs in China in 2006 [12]. This difference could be attributed to population increases, aging infrastructure, and the introduction of stricter discharge limits for newly built or upgraded WWTPs [29].

Table 3
Energy consumption of selected WWTPs at different percentiles.

Energy consumption	Percentiles					Mean	Standard deviation
	10th	20th	50th	80th	90th		
E_O (kWh/kg)	0.553	0.863	1.391	2.237	3.089	1.860	2.637
E_V (kWh/m^3)	0.099	0.161	0.256	0.374	0.465	0.296	0.280

When compared with the average for developed countries, the average E_V was mostly less than those of WWTPs in Netherlands (0.36 kWh/m^3), Australia (0.39 kWh/m^3), United State (0.45 kWh/m^3), Switzerland (0.52 kWh/m^3), Spain (0.53 kWh/m^3), and Singapore (0.56 kWh/m^3) [19,30,31]. Furthermore, the organic matter concentrations in China's municipal wastewater is comparatively lower (Table 1) than those in developed countries, which corresponds to a lower average energy consumption in wastewater treatment [22,32,33]. The other reason may lie in the fact that, due to limited economic input, the effluent quality of wastewater treatment in China may be poorer than those in the developed countries, so that treated wastewater may not be directly reused [34,35].

Fig. 2 shows the energy consumption of selected WWTPs in the four regions of China. Fig. 2 illustrates that the mean values of E_O recorded for WWTPs in the Central and Western regions were lower, while those for the Eastern and Northeastern regions were higher than the national average (Table 3). The relatively higher energy consumption by WWTPs in the Eastern region reflects the fact that this area has more water treatment facilities that use the MBR technology and that the effluent standards are stricter. Furthermore, the higher energy consumption in the Northeast region may be attributed to the relatively lower average operation loading rate of only 83.1% than that of the national average of 86.8%. Also, the influent BOD concentration showed considerably higher variability than those of the other regions [36]. Nevertheless, for all the four regions, as the standard deviation of

Table 2
Correlations between daily energy consumption, daily TOD reduction and daily wastewater treatment volume of selected WWTPs.

Variable		Daily TOD reduction (kg)	Daily treatment volume (m^3)
Daily energy consumption, E_d (kWh)	Pearson correlation	0.873[a]	0.871[a]
	Sig. (2-tailed)	0.000	0.000
	N	2022	2022

[a] Correlation is significant at the 0.01 level (2-tailed).

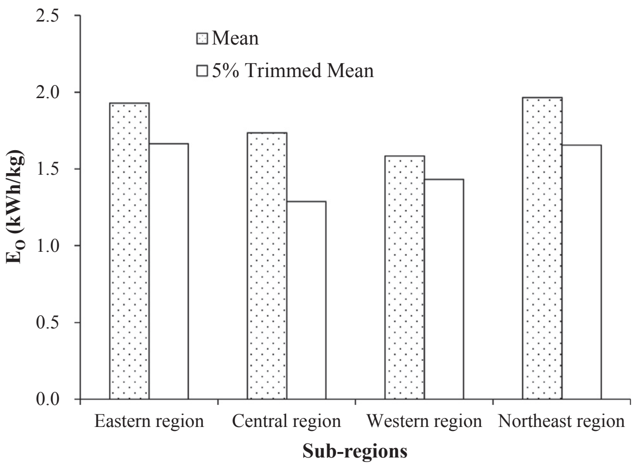

Fig. 2. Energy consumption per unit mass of TOD removal (E_O) for WWTPs in the four regions of China.

E_O decreases, the correlation between Δm, Q and E_d become stronger. For example, in the Western region, where the lowest standard deviation of E_O was recorded, the best proportionality relations were found between Δm, as well as Q, and the E_d with the proportionality coefficients of 0.938 kWh/kg ($R^2 = 0.943$) and 69.277 kWh/m^3 ($R^2 = 0.947$), respectively.

3.2. Influence of WWTP scale on E_O

The selected WWTPs were grouped into six categories according to the design capacity (10^3 m^3/d) as follows: < 10, 10–50, 50–100, 100–200, 200–500, and > 500. Table 4 shows that small- and middle-sized WWTPs, having treatment scales of less than 100×10^3 m^3/d dominated, whereby the number accounted for 90.7% of all WWTPs, and the actual capacity accounted for 53.9% of the total of all plants. The energy consumed by the small- (< 10×10^3 m^3/d) and medium-sized WWTPs was related to the treatment capacity, accounting for 56.4% of the total energy consumption of all WWTPs, and thus, leading to a considerable total energy consumption, which should definitely be reduced.

Fig. 3 demonstrates that the treatment energy requirement of a WWTP declines as the scale increases. Even within a size category, variations in energy requirements is large and is driven by several factors, including the type of treatment and source water quality. Similar results have been reported in Japan, Slovakia and other countries that large WWTPs are more energy efficient than small ones [37]. Fig. 3 also shows that E_O (mean and 5% trimmed mean for each category) has scale effects, that is, the larger the processing scale is, the lower the energy cost per unit of wastewater treated. This can be due to: (1) exploitation of economies of scale by using large and generally more efficient equipment, in particular, larger pumps and compressors; (2) ensuring that the process operates at more stable conditions, which is reflected on a more regular operation of electromechanical equipment and avoiding energy-intensive transitional periods; (3) more and especially better trained staff operating large plants, which is seldom the case for small WWTPs [21]. These results may explain why the capacities of newly constructed WWTPs have been increasing significantly, both locally and internationally.

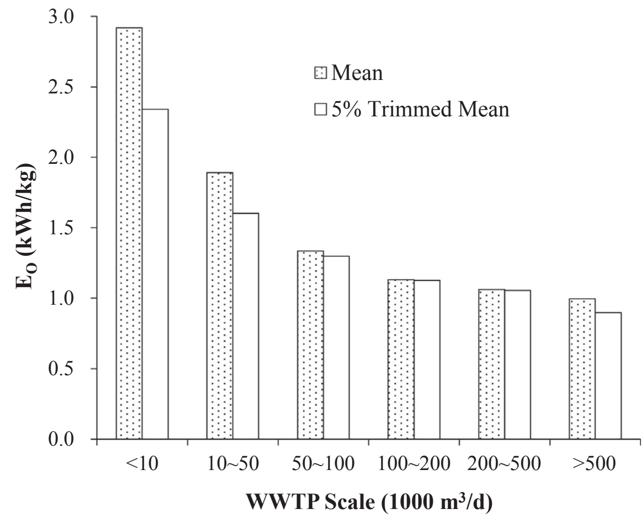

Fig. 3. Variation of energy consumption per unit mass of TOD removal (E_O) with WWTP scale in China.

Furthermore, Fig. 3 shows that the mean E_O of WWTPs in the scale range of 10–50 × 10^3 m^3/d approaches that of the national average because the number, actual capacity and energy consumption of the WWTPs were at the maximum (Table 4). In contrast, at the WWTP scale of less than 10×10^3 m^3/d, the mean value of E_O exceeds that of the national average, indicating that there is room for energy saving in small- and medium-sized WWTPs, and particularly, in small WWTPs.

In addition, energy consumption by WWTPs was not only related to the treatment capacity but was also influenced by operation loading rate and TOD removal. As shown in Table 4, with an increase in loading rate and TOD removal, the overall energy consumption diminishes as the scale of the WWTPs increased. The average loading rate and TOD removal of the small- and medium-sized WWTPs were lower than the national average values for WWTPs. As the small- and medium-sized WWTPs tend to be located in small towns with small populations, the volume of wastewater can vary considerably, and the wastewater collection systems are mostly incomplete, resulting in lower loading rates. On the other hand, the effluent quality from these WWTPs is often low, and the TOD removal is also low because they operate below capacity. Therefore, the average energy consumption of WWTPs in China is higher than it should be because of the large number of small- and medium-sized WWTPs that consume considerable energy and operate below capacity. This further illustrates the need to reduce the energy consumption of small- and medium-sized WWTPs.

3.3. Influence of WWTP loading rate on E_O

The operation loading rates of the selected WWTPs (Table 1) vary

Table 4
Characteristics of WWTPs in China in different scale ranges.

Parameter	WWTP scale (×10^3 m^3/d)					
	< 10	10–50	50–100	100–200	200–500	> 500
Number of WWTPs	210	1325	299	130	47	11
Total actual capacity (10^6 m^3/d)	0.79	28.04	21.36	18.50	14.78	9.63
Daily energy consumption (10^6 kwh/d)	29.3	730.9	528.1	434.4	345.6	217.4
Operation loading rate (%)	77.2	80.7	86.6	89.9	96.4	88.5
TOD removal (%)	87.7	88.6	91.9	91.6	91.6	93.2

widely, with an average of approximately 86.8%. To explore the relationship between energy consumption and loading rate (R, %), the selected WWTPs were grouped into seven categories according to their loading rates, as shown in Fig. 4. The findings indicate that 17.3% and 3.7% of WWTPs are operated at R < 60% and R > 120%, respectively, which altogether accounts for 9.8% of the total treatment capacity of all WWTPs and 11.3% of the total energy consumption by WWTPs in China. Over 80% of all WWTPs operate at loading rates ranging between 60% and 120%, which jointly account for over 80% of the total energy consumption and scale of WWTPs. This finding partly corroborates previous reports that the utilization of WWTPs in China was well within the design limits [38]. Additionally, circa 41.5% of the WWTPs are operated at loading rates of 80–100%, with 51.7% of the wastewater being treated and constitutes 50.6% of the total energy consumption. The loading rates in 16.0% of the WWTPs exceed 100%, with total treated wastewater and tantamount energy consumption of 25.8% and 22.4%, respectively. Furthermore, Fig. 4 shows that when R < 100%, the number, treatment capacity, and total energy consumption of the WWTPs increased as the operation loading rate also increased.

Fig. 5 indicates a decrease in the energy consumption of the WWTPs with increasing loading rate. WWTPs receiving lower loading rates than the design values present a significantly worse energy performance, but the energy consumption decreases as loadings approach the optimal value of 100% and decrease even further in overloaded plants. Considering the 5% trimmed means of E_O, specific energy consumptions of 3.90, 2.94, 2.13, 1.67, 1.57, 1.17 and 1.10 kWh/kg TOD removed were obtained as the loading rate increased from R ≤ 20% to R > 120%, respectively. In particular, long-term low loading rates increases the energy consumption of the treatment process. Overall, it can be seen (Fig. 5) that at R ≤ 20%, the E_O is significantly higher than all the other loading rate categories. Moreover, at the loading rate of less than 80%, the E_O for the WWTPs are higher than the national average and decrease significantly as the loading rate increases. In contrast, at R > 80%, the energy consumption decreases gradually to a level lower than the national average. However, overloading of the operation decreases the wastewater treatment performance, to a large extent, especially in terms of N and P and other pollutants removal [7]. Therefore, an optimal range of loading rate for WWTPs of 80–100% is recommended. When the WWTPs loading rates are approaching the optimal value, equipment and devices operated during the process can work more efficiently. Additionally, the treatment environment is relatively more stable with minimal changes in the amount of wastewater and pollutants concentration, thus providing better conditions for the growth of microorganisms in the sludge and saving energy.

3.4. Influence of treatment process on E_O

At present, a wide variety of wastewater treatment processes are used in WWTPs in China. The predominant ones include anaerobic-anoxic–oxic (A^2/O), oxidation ditch (OD), sequencing batch reactor (SBR), anoxic–oxic (A/O), membrane bio-reactor (MBR), BIOLAK, biofilter, wetland, oxidation pond, biological contact oxidation, activated sludge, and fluidized bed, among others. For our analysis, the selected WWTPs were grouped into A^2/O, OD, SBR, A/O and others, as shown in Fig. 6. It can be seen that OD was the most widely used technology, with 32.8% of WWTPs adopting this technology. The second most popular technology was A^2/O with an adoption rate of 32.5% and the third was SBR with an adoption rate of 16.5%, which was followed by A/O with an adoption rate of 6.78%. The activated sludge process, which has been employed extensively in both its conventional and modified forms, accounted for 93.2% of all WWTPs. As for the design capacity, the A^2/O technology accounted for the biggest design treatment capacity of 42.8%, followed by OD with 23.4%, then the SBR with 11.5%, and that of A/O with 10.7%. Energy consumption by A^2/O, OD, SBR and A/O technologies accounted for 43.4%, 22.5%, 10.2% and 11.8% of the total energy consumption by all WWTPs, respectively. Similar findings on quantity and treatment capacity of WWTPs were reported by the Ministry of Housing and Urban-Rural Development of the People's Republic of China [9].

Different wastewater treatment technologies may have different energy consumption rates because of the differences in specific wastewater treatment processes [30]. The means and 5% trimmed means of E_O for the four main wastewater treatment processes are presented in Table 5, and ranked in order of A/O > A^2/O > OD > SBR. Compared with the A^2/O systems, the A/O systems have higher energy demand due to the lower loading rates. With longer hydraulic retention time (HRT) and lower TOD removals, OD systems are expected to have higher energy requirements. However, the OD systems recorded lower energy consumptions than the A^2/O systems due to the higher loading rates. Thus, the energy consumption in these systems is strongly influenced by the loading rate. In contrast, it was previously reported that the energy consumed by SBR plants is influenced not by loading rate but by design capacity [12]. Therefore, the lower energy consumption recorded in SBR systems is attributable to the large number of small- and medium-sized WWTPs, about 95.2% of which is made up of SBR plants.

The selection of treatment processes depends on multiple factors including treatment efficiency, energy efficiency, cost, and land availability. Tables 3 and 5 show that the total energy consumption by the OD was close to the national average, whereas that for the A/O and A^2/O were significantly greater than the national average. In contrasts, the total energy consumed by the SBR processes was less than the national average. Therefore, since small and medium-sized cities have lower levels of economy and management, OD and SBR may offer several advantages. Without primary settling or secondary sedimentation tanks, the infrastructure construction is simple, and the management is convenient. Therefore, as to the small-scale and medium-scale WWTPs, OD and SBR and their modified processes, such as CAST (Cyclic Activated Sludge Technology), DAT-IAT (Demand Aeration Tank-Intermitted Aeration Tank), UNITANK, and ICEAS (Intermittent Cyclic Extended Aeration System) processes [39], are recommended as the best choices.

3.5. Influence of TOD removal on E_O

To explore the relationship between energy consumption and the TOD removal in wastewater treatment plants, the calculated TOD removals were grouped into five categories, namely from 100% to 90%, from 90% to 80%, from 80% to 70%, from 70% to 60%, and less than or equal to 60%. At present, 88.6% of WWTPs are operated at TOD removal greater than 80%, which jointly accounts for 92.8% of the total

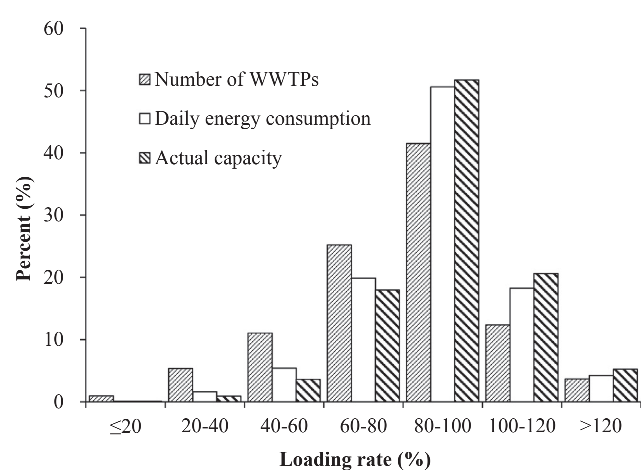

Fig. 4. Distribution of WWTP number, treatment capacity, daily energy consumption and loading rate.

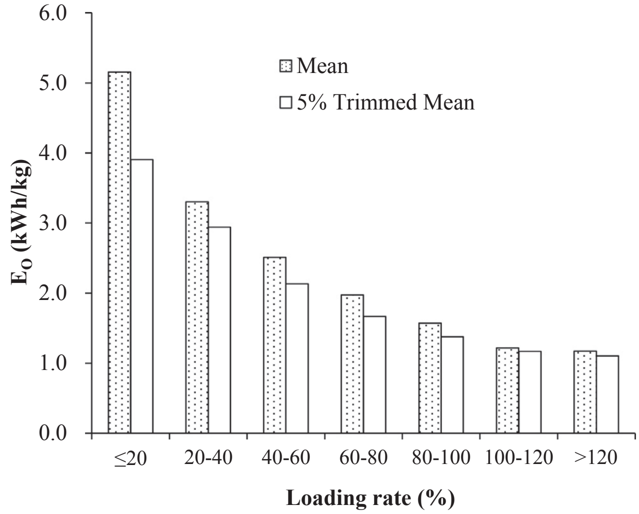

Fig. 5. Variation of energy consumption per unit mass of TOD removal (E_O) with WWTP loading rate in China.

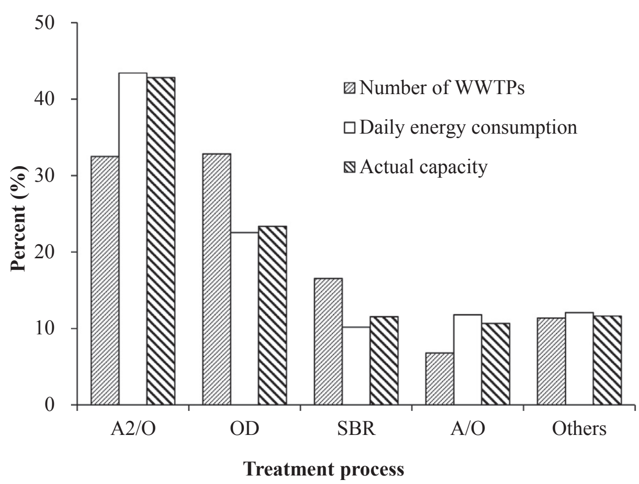

Fig. 6. Distribution of wastewater treatment processes applied in the selected WWTPs.

Table 5
Comparison of the main treatment processes adopted in the selected WWTPs.

Parameter	Main treatment processes			
	A^2/O	OD	SBR	A/O
WWTP number	657	664	334	137
Total actual capacity (10^6 m^3/d)	39.86	21.76	10.73	9.93
Operation loading rate (%)	86.0	89.0	85.2	83.4
TOD removal (%)	91.5	88.3	89.9	88.2
Mean of E_O (kWh/kg)	1.904	1.854	1.697	1.960
5% trimmed mean of E_O (kWh/kg)	1.609	1.494	1.489	1.674

treatment capacity of all WWTPs and 93.7% of the total power consumption. Additionally, 60.7% of the WWTPs have TOD removals of 90–100%, which treats 69.1% of all the wastewater and accounts for 73.1% of the energy consumed. These findings indicate that the pollutant removal performance of WWTPs in China was satisfactory.

The E_O index for the different TOD removal ranges was also examined. Fig. 7 shows that the energy consumption of the WWTPs decreased as the TOD removal increased. WWTPs having lower TOD removal present a significantly worse energy performance, whereby energy consumption decreases when approaching the optimal TOD removal of 100%. Overall, at TOD removals of less than or equal to 60%, the mean value of E_O is significantly higher than all other TOD removal categories. This variation may be attributed to the extremely low operation loading rates recorded in this category. Compared with the category with TOD removals ranging between 70% and 80%, the mean value of E_O for the category with TOD removals of between 80% and 90% have higher energy demand due to the larger number of small-sized WWTPs that fall within this category. Moreover, the mean value of E_O for WWTPs that achieved TOD removals between 90% and 100% was lower than that of the national average, because the optimal range of loading rate increased. Since an improved energy-efficiency usually concurs with more effective treatment and operation, a higher TOD removal is apparently more favorable for efficient energy consumption.

3.6. Advantages of using E_O for evaluating WWTP energy consumption

The method for calculating TOD explained in Section 2.2 indicates that the TOD contributed by organic pollutants was based on the equivalent mass of O_2 consumed for BOD removal (1 g O_2 for 1 g BOD removal) while the TOD contributed by NH_4^+-N was evaluated based on the stoichiometric relation shown in Eq. (1) (4.18 mg O_2 for 1 mg NH_4^+-N removal). The average influent BOD_5 and NH_4^+-N for the 2022 WWTPs investigated in this study were 109.5 mg/L (or g/m^3) and 25.6 mg/L (or g/m^3), respectively. Conversely, the average effluent BOD and NH_4^+-N after treatment were 8.1 mg/L and 3.2 mg/L, respectively. Therefore, the average TOD removal could be simply calculated as follows:

$$\Delta TOD = (109.5 - 8.1) + 4.18 \times (25.6 - 3.2) = 195.03\ g/m^3 \quad (7)$$

of which 101.40 g/m^3 (52%) was contributed by BOD removal and 93.63 g/m^3 (48%) was contributed by nitrification of NH_4^+-N.

Further in-depth analysis of the data from the 2022 WWTPs demonstrated that the influent BOD and NH_4^+-N vary widely in different WWTPs and the mass ratio of BOD to NH_4^+-N ranges between 1.0 and 30. The relationship discussed above indicates that the contributions of BOD and NH_4^+-N to the TOD can range between 88% versus 12% and 19% versus 81%. If the traditional energy indices based on only the BOD and COD removal are adopted for the energy efficiency evaluation, the energy consumed for nitrification will inevitably be significantly underestimated especially in the cases of very low BOD/NH_4^+-N mass ratios. The introduction of the novel energy index E_O based on TOD calculation can thus assist a more rational assessment of the true oxygen demand for the removal of different oxygen-consuming pollutants.

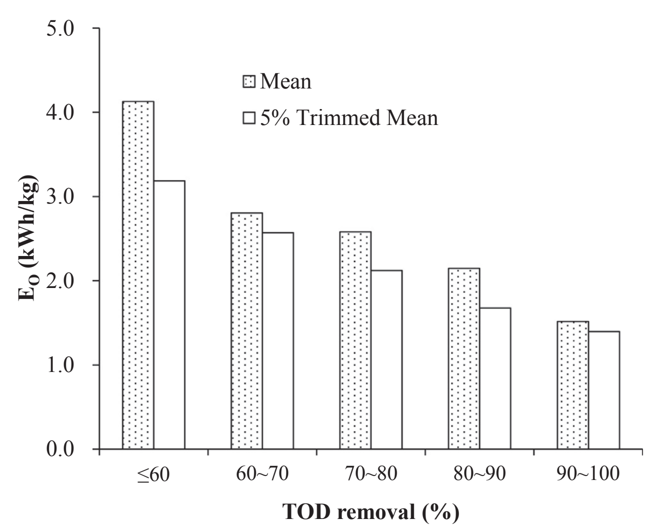

Fig. 7. Variation of energy consumption per unit mass of TOD removal (E_O) with TOD removal in selected WWTPs in China.

The most common index currently employed for energy consumption assessments is E_V calculated on the basis of treated wastewater volume. An evaluation of the influence of WWTP scale, loading rate, and treatment processes on both E_O and E_V as shown by the data presented in the Supplementary Information demonstrate that E_V can provide a proper evaluation of the energy efficiency of WWTPs only when the influent quality and the target of pollutants removal do not show considerable variations. However, regarding the removal of the total oxygen-consuming pollutants, namely TOD, in contrast to Fig. 7 showing a significant decrease of E_O with increasing TOD removal, E_V tended to increase slightly with increasing TOD removal (Fig. S4 in the Supplementary Information). This increase in E_V is because a higher removal of the oxygen-consuming pollutants needs a higher energy input to provide sufficient oxygen for the same volume of the wastewater to be treated. Nonetheless, the increased energy input resulted in more efficient TOD removal as indicated by the decreasing E_V (Fig. 7). Therefore, E_O can assist a more comprehensive evaluation of energy consumption from the standpoint of pollutants removal, which is the essential objective of wastewater treatment.

4. Conclusions

Because WWTPs are energy intensive, a comprehensive evaluation of energy consumption is often required in finding ways to improve energy efficiency. Considering that aeration usually consumes up to 75% of the total energy input, a novel index of TOD is developed for characterizing the main pollutants that consume oxygen in WWTPs. The TOD comprises not only the oxygen demand for organics decomposition (as indicated by BOD or COD) but also the oxygen demand for nitrification to transform ammonia-nitrogen to nitrate-nitrogen. The nitrification process is found to consume almost the same mass of oxygen as that for organics decomposition, according to calculations based on data in China. TOD was thus proved to be a comprehensive indicator to characterize the majority of the oxygen-consuming pollutants in WWTPs. On this basis, an energy consumption index E_O was further developed, which measures the energy consumed per unit mass of TOD removal. An evaluation of WWTPs in China using this novel energy consumption index demonstrated that WWTP scale, loading rate, and more importantly the TOD removal were major factors to influence energy consumption efficiency. Larger WWTPs with reasonably higher loading rates and higher TOD removal would be more energy efficient. However, centralized wastewater treatment may not always be appropriate for urban development and so measures have to be identified to improve the energy efficiency for small- and medium-sized WWTPs. An evaluation of several technologies and systems using the E_O indicator showed that SBR was more energy efficient than other biological processes widely applied in smaller scale WWTPs in China. Therefore, proper selection of treatment process, rational design of the treatment system to achieve a high TOD removal, and optimal operation of the system to maintain a reasonably high loading rate can considerably improve WWTP energy consumption efficiency.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2018.11.101.

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