Assessment of Energy-Positive Wastewater Treatment System Design of Different Industrial Wastewater Streams

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Abstract

Activated sludge (AS) process has been used as the conventional industrial wastewater treatment process in the past decades. However, intensive aeration requirements made it impossible for WWTPs to be energy positive. In addition, there are few cases of research assessing the efficiency and economic feasibility of innovative technologies in treating industrial wastewater to achieve energy positive. This study tries to assess the effect of different kinds of industrial wastewater on treatment efficiency, unit energy, environmental sustainability, and unit cost of treatment systems using innovative technologies such as micro sieving, UASB, and PN/A. Our Excel model showed that micro-sieving could remove 32.50-39.72% of COD from industrial wastewater. UASB reactor could removes 15.8%-53.5%, 14.0%-49.0% and 22.9%-51.0% of COD from three different wastewater streams. Mean unit energy production by the innovative system could reach 1.80, 1.77, and 1.73 kWh/kg $BOD_{removed}$, respectively. The average unit cost of three kinds of wastewater is 0.54, 0.57, and 1.12 \$/kg $COD_{removed}$, respectively. Treating meat processing wastewater with innovative technologies is the economical treatment method. However, this method could not be considered as the sustainable design due to the high effluent COD concentration. The economic advantages and limitations of innovative technologies in treating industrial wastewater have been quantified by energy, cost and environmental indicators. These metrics provide valuable references for future sustainable design of industrial wastewater treatment systems.

Keywords: Meat processing wastewater; Tannery wastewater; Textile wastewater; COD removal; Cost estimation Excel model

1. Introduction

Industrial wastewater has vastly different water quality. For example, the water quality of food processing, pulp and paper, textile, chemical, pharmaceutical, petroleum, tannery, and manufacturing industries varied significantly [1]. Major wastewater quality parameters include chemical oxygen demand (COD), biochemical oxygen demand (BOD), suspended solids (SS), ammonium nitrogen ($\text{NH}_4^+ \text{--} \text{N}$), heavy metals, pH, color, turbidity, and biological parameters. Compared with municipal wastewater, industrial wastewaters usually have a high organic matter concentration and extreme physicochemical characters (e.g., pH, temperature, salinity), and humic substances that may inhibit biological treatment processes. In addition, municipal wastewater has a low strength concentration of COD (250–800 mg/L), whereas strong (>1,000 mg COD/L) to extremely strong wastewaters is often produced by industries [2]. Olive mills and beverage production industries could generate extremely strong industrial wastewaters (COD>200,000 mg/L) [3, 4]. Characteristics of industrial wastewaters strongly depend on the type of industrial wastewaters and industrial processes. Water used by meat processing industries accounts for 29% of the agricultural freshwater worldwide [5, 6]. Food processing wastewater is typically generated from the slaughtering houses. Typically, there is a large quantity of suspended organic matter, protein, and fat (i.e., bones, meat, and viscera) in meat processing wastewater. Therefore, a high concentration of COD, BOD, TN, and TSS is typical in food processing wastewater [7-9]. The average COD, BOD, TN and TSS concentration of food wastewater could reach as high as 4,221 mg/L, 1,209 mg/L, 427 mg/L, and 1,164 mg/L, respectively [10]. Meat processing wastewater is considered as one of the most detrimental food industrial wastewaters because its inadequate disposal could lead to river deoxygenation, algal blooms, and eutrophication [11, 12].

The tannery industry, which could be defined as the production process of leather by treating sheep and goat skins and bovine hides, is one of the oldest industries worldwide [13]. Leather is one of the few available materials to produce clothing and footwear because of its unique properties [14]. However, tannery industry consumes large amounts of water and chemicals. Wastewaters are mainly produced during the wet processes of tannery industry. To produce 250 kg of leather, 15–80 m³ of tannery wastewater with 230–250 kg COD, 100 kg BOD, 150 kg TSS, 5–6 kg chrome, and 10 kg sulphide is produced [15, 16]. Tannery effluents are characterized by high pollution loads of conventional pollutants and suspended solids with low BOD/COD ratio, which cause deterioration of the receiving natural water bodies if it were inadequately treated [17-24].

Textile industry, representing one of the largest and most widespread production industries in the world, produces a large number of dyestuffs ($>7 \times 10^5$ tons) per year worldwide [25]. Textile industry produces a large amount of processing wastewater containing variety of chemicals. For example, wastewater with dyestuff, surface-active agents, and additives are generated from spent dye bath and rinsing waters [26-28]. Textile effluent is typically a complex mixture of organic and inorganic matters with strong color, high COD, high salinity, high temperature, variable pH, and low BOD [29, 30]. The direct discharge of textile wastewater into rivers and streams could cause severe environmental problems [31]. Commercial dyes in textile effluent are carcinogenic to humans and toxic to aquatic organisms [27, 32-34]. The discharge of untreated textile wastewater deteriorates water quality, adversely impacts aquatic life and crops [35-37].

Biological and chemical processes are traditionally used in treating meat processing, tannery, and textile wastewater [38-58]. Physical and chemical methods

are very expensive because they consume a large amount of energy and chemicals with excessive sludge [59-61]. Compared with oxidation process and chemical processes, biological treatment methods have numerous advantages: (1) low capital and operating costs; (2) oxidation of a wide variety of organic matters rather phase transfer separation such as air stripping or carbon adsorption; (3) removal of reduced inorganic compounds, such as ammonia, and total nitrogen removal by nitrification and denitrification; and (4) operational flexibility to treat different kinds of wastewater with a wide range of flows.

The unit energy consumption of meat processing plants using biological process was reported as 0.81 kWh/kg COD [62]. Yang et al. [63] compared the performance and energy of textile wastewater treatment by conventional activated sludge (CAS), MBR, and Moving bed biofilm reactor (MBBR). Results showed that the unit energy consumption of CAS is 0.58 kW/kg COD. Activated sludge (AS) system with autotrophic nitrification/heterotrophic denitrification (NDN) process with primary clarifier were conventional processes in industrial and municipal wastewater treatment. However, they consume high energy, have large footprints, and produce a large amount of sludge as compared with innovative biological technologies such as micro sieving, UASB, and PN/A, which are the major focus of this study.

Micro-sieving is one of the most sustainable technologies in separate TSS from wastewater stream at the early stage of treatment processes. As a result, it significantly reduces operation costs and has less footprint. Mainstream UASB could achieve energy recovery by converting COD to biogas without consuming O₂ at operating temperatures between 15 and 35°C [64, 65]. PN/A, which is an innovative N removal technology discovered in the 1990s [66-68], could remove 90% of NH₄ -N through converting ammonia and nitrite N₂ in Anammox process [69-72]. Compared with the

conventional nitrification/denitrification (NDN) process, PN/A process could reduce O_2 demand during nitrification by approximately 60%, eliminate external organic carbon source, and decrease sludge by 80-90% [73-75]. Currently, there are few cases of research assessing the efficiency and economic feasibility of innovative technology in treating different kinds of industrial wastewater. Therefore, the effects of different kinds of industrial wastewater on the performance, energy, and cost of using micro-sieving, UASB, and PN/A were quantified from energy, cost, and sustainability metrics. The objectives of this study are to (1) evaluate the influence of different industrial wastewater on the performance of primary treatment and secondary treatment; (2) compare the unit energy consumption of different industrial wastewater treatment with the energy benchmark value of PN/A; (3) analyze the unit cost of the innovative treatment systems in treating three different industrial wastewater streams. In addition, the economic advantages and limitations of innovative technologies in treating different industrial wastewater are addressed to offer insight into sustainable treatment design of different industrial wastewaters.

2. Material and methods

2.1 Data and process flow

In the current study, energy and cost were calculated based on three different kinds of industrial wastewater streams, namely, meat processing, tannery, and textile wastewater. Wastewater quality data were collected from published peer-reviewed papers as shown in Table 1. Database of untreated wastewater quality included the concentrations of TSS, COD, BOD, and $NH_4^+_N$. The concentration of TSS, COD, BOD, and $NH_4^+_N$ of meat processing wastewater is higher than those of tannery wastewater and textile wastewater.

An Excel-based model was developed. One million gallons per day (MGD) wastewater treatment systems with different primary and secondary treatment processes were designed [76-81]. Figures 1 and 2 show the flow diagram of industrial wastewater treatment systems. In all systems, the screen and grit chamber were used as the preliminary treatment in removing large particulate matter from wastewater. The difference between systems is the primary and secondary treatment processes. In systems A and B, primary clarifier and micro-sieving removed particulate COD and N and produced a certain amount of primary sludge, which results in the performance difference of aerobic treatment, UASB, PN/A reactor, and side stream AD design. The nitrification-denitrification process was used as the main system of system A in treating wastewater to meet the discharge requirement by converting biodegradable COD and N to CO₂ and N₂. System B used mainstream UASB and PN/A as the main processes in removing soluble BOD and N, which reduces aeration consumption through decreasing BOD and N loading to the nitrification-denitrification system. To meet discharge requirements and compare the performance of the wastewater treatment system for different industrial wastewater, system B use UASB, PN/A, and NDN to achieve the same effluent BOD and N concentration as system A.

Table 1 Industrial Wastewater quality

Type of wastewater	TSS	BOD	COD	TN	Reference
Meat processing wastewater	950.00	1200.00	2100.00	220.00	[82]
	1400.00	1070.00	2350.00	317.22	[83]
	1164.00	1209.00	4221.00	427.00	[10]
	662.00	891.00	1697.00	246.00	[84]
	625.00	1320.00	3900.00	217.00	[85]
	3438.22	1602.00	5422.25	361.25	[86]
Tannery wastewater	890.00	665.83	2,290.00	282.00	[87]
	2,690.00	1,470.00	3,700.00	293.93	[13]
	915.00	1,024.89	2,155.00	228.00	[13]
	1,147.00	1,126.00	3,114.00	131.70	[13]
	2,229.00	1,760.00	5,094.00	358.00	[88]
	1,150.00	1,746.00	6,240.00	327.00	[89]
Textile wastewater	1,550.00	463.25	3,280.00	260.00	[87]
	137.00	455.00	1411.00	49.20	[90]
	324.00	283.00	513.00	28.70	[91]
	150.00	150.00	910.00	40.00	[92]

	460.00	198.00	714.00	18.70	[93]
	520.00	225.00	770.00	23.00	[93]
	438.00	220.00	798.00	24.70	[93]

Figure 1 Schematic graphs of wastewater treatment system A- activated sludge process with nitrification-denitrification

Figure 2 Scheme of wastewater treatment system B: UASB and anammox treatment

2.2 Equations for estimating energy, cost and environmental indicators

2.2.1 Energy production of anaerobic digestion

Wastewater quality, retention time, temperature affects COD removal and methane production of UASB. Research by Cavalcanti et al. [94] yielded detailed empiric equations that can be used to predict the division of the influent COD over the effluent based on wastewater quality, sludge age, and temperature.

$$m_{Seu} = f_{ns} + 0.27 \cdot \exp[-0.04 \cdot (R_{su} - 4)]/1.067^{T-25} \quad (1)$$

$$m_{Sxvu} = f_{np} + f_{cv} \cdot Y_{an} \cdot (1 - f_{ns} - f_{np}) + 0.25 \cdot \exp[-0.04 \cdot (R_{su} - 4)]/1.067^{T-25} \quad (2)$$

$$m_{Sdu} = 1 - m_{Seu} - m_{Sxvu} \quad (3)$$

where:

m_{Seu} = fraction of influent COD ending up as non-settleable COD in the UASB effluent (g COD/g COD)

m_{Sxvu} = influent COD fraction converted into anaerobic excess sludge (g COD/g COD)

m_{Sdu} = fraction of influent COD digested in UASB (g COD/g COD)

T =temperature=25°C

f_{ns} = non-biodegradable, soluble influent COD fraction (g COD/g COD)

f_{np} = non-biodegradable particulate influent COD fraction (g COD/g COD)

R_{su} = anaerobic sludge age in the UASB reactor

Yan = yield coefficient in an anaerobic environment (0.05 g VSS/g COD) as determined by Cavalcanti et al. [94]

Since the sludge age of UASB is greater than 20 to 40 days [76], sludge age is assumed to be 40 d. Since biodegradable COD in wastewater could be converted into CH₄ at 15 and 35°C [64], operating temperature of treatment system was assumed to be 25 °C.

$$\begin{aligned} \text{Energy production of UASB (kWh/d)} &= (mS_{du}) (Q_{UASB})(S_{UASB}) (0.25 \text{ g CH}_4/\text{g COD}) \\ &\quad (10^{-3}\text{kg/g})(13.9 \text{ kWh/kg CH}_4) (38\%) \end{aligned} \quad (4)$$

Theoretical unit energy production of UASB (kWh/kg COD_{removed})

$$= \frac{\text{Energy production of UASB (kWh/d)}}{\text{COD removal in UASB (kg/d)}}$$

(5)

where:

mS_{du} = fraction of influent COD digested in UASB (g COD/g COD)

S_{UASB} = Influent COD concentration to UASB (g/m³)

Q_{UASB} = Flow rate to UASB (m³/d)

COD removal in UASB (kg/d) = COD digested in UASB + COD discharged as sludge

Qasim and Zhu [95] reported that 1 kg COD could be converted to 0.25 kg CH₄ by UASB. It was assumed that UASB combining the heat and power (CHP) technologies could convert 38% of CH₄ formed in the anaerobic digestion to electricity with an energy density of approximately 13.9 kWh/kg CH₄ [77].

$$RT_{AD} = 15\text{d}$$

(6)

$$T_{AD} = 35^\circ\text{C}$$

(7)

$$\eta_{AD}=0.7 \quad (8)$$

where:

RT_{AD} = sludge retention time in the high-rate digester (d)

T_{AD} = operation temperature (°C) in the high-rate digester

η_{AD} = biodegradable COD destruction value

Since combined heat and power (CHP) could convert the CH_4 formed in anaerobic digestion to heat to run an anaerobic digester at high temperature, operation temperature is assumed to be 35 °C in the anaerobic digester. Side stream high-rate anaerobic digester converted sludge to CH_4 in the absence of air at a specific solids retention time and a specific temperature. Mean values of solids retention time and temperature shall be between 15 days at 35°C to 55 °C and 60 days at 20°C [96]. Kabouris et al. reported that the biodegradable volatile solids destruction value of anaerobic digester was 69% at a retention time of 12 days and 35°C [97]. It was reported 70% of biodegradable COD could be converted to CH_4 at 35°C [77]. As a result, retention time, temperature and biodegradable COD destruction value of the high-rate digester are assumed to be 15d, 35°C and 70%.

2.2.2 Energy consumption of PN/A

The reaction of the PN/A process can be depicted as the following equation [95]:

$$NH_4^+ + 0.799 O_2 + 1.109 HCO_3^- \rightarrow 0.436 N_2 + 0.111 NO_3^- + 1.034 CO_2 + 2.496 H_2O + \text{New biomass}$$

$$(9)$$

The overall oxygen requirement for conversion of ammonia to nitrogen gas and nitrate is 1.83 g O_2 /g NH_4-N converted.

$$\begin{aligned}
& \text{Theoretical unit energy consumption of PN/A} = \frac{1.83 \text{ kg O}_2/\text{kg NH}_4\text{-N}}{\text{OT}_a} \\
& = 1.32 \text{ kWh/kg NH}_4\text{-N}
\end{aligned}
\tag{10}$$

where:

$$\text{OT}_a = \text{Oxygen transfer efficiency (actual)} = 1.2 \text{ kg O}_2/\text{kWh [76]}$$

Since biodegradable COD in wastewater could be converted into CH₄ at 15 and 35°C [64], the operating temperature of the treatment system was assumed to be 25 °C. Therefore, energy consumption is estimated based on O₂ mass demand and oxygen transfer efficiency at 25 °C [76].

2.2.3 Unit energy of WWTP

The following equations were used in calculating the unit energy consumption, and production [76, 77]:

$$\begin{aligned}
& \text{Unit electricity consumption (kWh/m}^3\text{)} \\
& = \frac{\text{Aeration demand of PN/A and NDN (kgO}_2\text{/d)}}{\text{Oxygen transfer efficiency (actual)Q}}
\end{aligned}
\tag{11}$$

$$\begin{aligned}
& \text{Unit electricity consumption (kWh/kg N}_{\text{removed}}\text{)} \\
& = \frac{\text{Aeration demand of PN/A and NDN (kgO}_2\text{/d)}}{\text{Oxygen transfer efficiency (actual)(N removal (kg/d))}}
\end{aligned}$$

where Q=flow rate (m³/d)

$$\text{Oxygen transfer efficiency (actual)} = 1.2 \text{ kg O}_2/\text{kWh}
\tag{12}$$

$$\begin{aligned}
& \text{Energy production (kWh/d)} = (\text{Electricity recovery}) (\text{Enthalpy of combustion}) (\text{CH}_4 \\
& \text{production from UASB and anaerobic digester (kg/d)})
\end{aligned}$$

where Electricity recovery=38%

Enthalpy of combustion=13.9 kWh/kg CH₄

(13)

$$\text{Unit energy production(kWh/kg BOD}_{\text{removed}}) = \frac{\text{Electricity production(kWh/d)}}{\text{BOD removal (kg/d)}}$$

(14)

It was assumed that UASB combining the heat and power (CHP) technologies could convert 38% of CH₄ formed in the mainstream and the side stream anaerobic digestion to electricity with an energy density of approximately 13.9 kWh/kg CH₄ [77]. The energy demand of a WWTP mainly includes power consumption of the wastewater lift pump, aeration equipment, and sludge treatment. The energy consumption of biological treatment accounts for 50–70% of the overall energy consumption [98]. Since UASB removes COD without consuming oxygen, aeration energy of PN/A, and NDN process was the dominant energy demand. Biodegradable COD in wastewater could be converted into CH₄ at 15 and 35°C [64], the operating temperature of the treatment system was assumed to be 25 °C. Therefore, energy consumption is estimated based on O₂ mass demand and oxygen transfer efficiency at 25 °C [76].

2.2.4 Environmental indicators

Many studies selected global warming and eutrophication potential to assess the environmental performance of wastewater treatment systems [99-101]. In the current study, the effluent wastewater quality, energy consumption and energy production were converted to environmental indicators per volume of treated wastewater based on table 2. These two environmental indicators were selected to evaluate the impact of different industrial wastewaters on environmental sustainability metrics of the innovative treatment technologies.

Table 2 Effluent wastewater quality, energy, and corresponding environmental indicators

Parameter	Global warming potential (kg CO ₂ eq/m ³)	Eutrophication potential (kg PO ₄ ³⁻ eq/ m ³)	Reference
Effluent COD (kg/ m ³)		0.022	[101]
Effluent nitrogen (kg/ m ³)		0.402	
Energy consumption (kWh/m ³)	0.591	0.00115	
Energy production (kWh/m ³)	-0.591	-0.00115	

2.2.5 Unit cost of WWTP

The following equations are used in calculating the unit capital cost and unit operation and maintenance (O&M) cost [76]:

Annualized capital cost(\$/yr) = Capital cost(\$) × Capital Recovery Factor (CRF)

$$CRF = \frac{1}{\text{annualization factor}} = \frac{1}{a_{i,n}} = \frac{i(1+i)^n}{(1+i)^n - 1}$$

where i =interest rate (annual)=6%

n=economic lifetime of the treatment plant in years=20 (yr)

The treatment system was financed through a 20-year loan with a fixed interest rate of 6%.

(15)

$$\text{Unit capital cost}(\$/\text{m}^3) = \frac{\text{Annualized capital cost}(\$/\text{yr})}{(Q)(365\text{d}/\text{yr})}$$

(16)

$$\text{Unit O\&M cost}((\$/\text{m}^3) = \frac{\text{Annual O\&M cost}(\$/\text{yr})}{(Q)(365\text{d}/\text{yr})}$$

where Q=flow rate (m³/d)

(17)

$$\text{Unit cost}(\$/\text{m}^3) = \text{Unit capital cost}(\$/\text{m}^3) + \text{Unit O\&M cost}((\$/\text{m}^3)$$

$$\text{Unit cost}(\$/\text{kg COD})$$

$$= \frac{\text{Annualized capital cost}(\$/\text{yr})}{(\text{COD removal (kg/d)})(365\text{d}/\text{yr})}$$

$$+ \frac{\text{Annual O\&M cost}(\$/\text{yr})}{(\text{COD removal (kg/d)})(365\text{d}/\text{yr})}$$

To compare the cost of treatment systems, the total capital costs (\$) were annualized over the expected lifetime of a WWTP. Economic lifetime and interest rate were assumed to be 20 years and 6% [76]. Capital costs (\$) were annualized capital costs (\$/yr) based on the interest rate and lifetime. The total unit cost was calculated as the summation of the unit capital and the unit O&M costs.

3. Results and Discussions

3.1 Impact of different industrial wastewater quality

3.1.1 Treatment performance of primary treatment

Pollutant concentration and flow rate determine the mass of the contaminants removed, whereas the performance of wastewater treatment equipment depends on characteristics of wastewater such as particulate matter fraction and biodegradability. TSS/COD ratio and BOD/COD ratio are widely used as indicators of these two different types of wastewater characteristics. Figure 3 compares these indicators of different industrial wastewater. It shows that the TSS/COD ratio of textile wastewater is higher than those of other industrial wastewaters. Due to relatively high TSS concentration, micro sieving shows TSS removal of greater than 50% and significantly higher COD removal than the primary clarifier, as shown in Figure 4. For tannery wastewater, meat processing wastewater, and textile wastewater, the average COD removal by micro sieving is 35.36%, 39.08%, and 32.50%, respectively, which are higher than that by primary clarifier. Textile wastewater has a relatively lower TSS concentration than other industrial wastewaters in Table 1. However, primary clarifier in textile wastewater treatment shows higher COD removal than tannery wastewaters due to the high TSS/COD ratio of textile wastewater, as shown in Figure 4. To assess the influence of wastewater quality on COD removal of the primary clarifier and micro

330 sieving, Pearson correlation analysis was carried out to evaluate the correlation between
 331 COD removal and related parameters at a level of significance of $p < 0.01$.

332

333 **Figure 3** TSS/COD ratio and BOD/COD ratio for different industrial wastewater

334

Figure 4 COD removal of primary treatment for different industrial wastewater

Table 3 shows the Pearson's correlations between COD removal of two systems, the concentration of TSS and TSS/COD. Compared with TSS concentration, the ratio between TSS and COD showed stronger positive correlations with COD removal at the 0.01 level. Therefore, regression models of COD removal are developed based on TSS/COD ratio. The trend lines for predicting COD removal of primary treatment from TSS/COD are depicted in Figure 5. TSS concentration of textile wastewater is lower than those of other industrial wastewaters. However, textile wastewater has a relatively low concentration of COD, as shown in Table 1. The particulate COD fraction of textile wastewater is higher than those of other industrial wastewaters. Since TSS/COD ratio is associated with particulate COD fraction, COD removal of two systems rises with the increasing TSS/COD ratio of influent wastewater as shown in Figure 5. Therefore, TSS/COD ratio is the key parameter for determining COD removal of primary treatment. Due to the high particulate matter fraction, primary treatment shows excellent separation performance during treatment of textile wastewater.

Table 3 Correlations between COD removal, TSS concentration, and TSS/COD ratio of influent wastewater

Pearson Correlation	COD removal of system A (%)	COD removal of system B (%)
TSS (mg/L)	0.278	0.595**
TSS/COD (%)	0.941**	0.910**

** At the 0.01 level (2-tailed), correlation is significant.

Figure 5 Variation of COD removal in primary treatment with TSS/COD ratio

Biodegradability expressed as the BOD/COD ratio represents the ability of a substance to be removed by microorganisms. It is a common index of wastewater biodegradation [102]. The higher the BOD/COD ratio, the higher is the biodegradability. Biodegradability of meat processing wastewater, tannery wastewater, and textile wastewater are shown in Figure 3 which illustrates the average BOD/COD ratio of 0.412, 0.327, and 0.314, respectively. Therefore, meat processing wastewater has higher biodegradability than other industrial wastewaters. Figure 6 shows the BOD/COD ratio of untreated wastewater and treated wastewater by primary clarifier and micro-sieving. Biodegradability rises with the increasing BOD/COD ratio of untreated wastewater. Figure 6 demonstrates that the slope of the linear fitting equation for system B is greater than that of system A, which illustrates that micro-sieving could improve the biodegradability of wastewater more significantly as compared with the primary clarifier. Primary treatment increases the biodegradability of wastewater by

reducing the particulate non-biodegradable COD fraction of industrial wastewater. As compared to system A, the BOD/COD ratio of wastewater increased by 0.59%-7.50%, 0.60%-3.57%, and 0.01%-2.19% for meat processing wastewater, tannery wastewater, and textile wastewater, respectively. Due to the relatively low TSS concentration of textile wastewater, TSS removal by primary clarifier and by micro sieving and variation of BOD/COD ratio is smaller. Meat processing wastewater has higher biodegradability and TSS concentration, micro sieving increases mean and maximum BOD/COD ratio to 0.48 and 0.63. Hence, the biodegradability of industrial wastewater with a high concentration of TSS is easier to be improved by micro-sieving.

Figure 6 Variation of biodegradability after primary treatment

3.1.2 Treatment performance of secondary treatment

Due to high COD removal of micro sieving and UASB reactor in system B, COD removal of aerobic treatment in system B decreases by 40.7%-66.5%, 33.6-60.0%, and 23.0%-60.0% for meat processing wastewater, tannery wastewater, and textile

wastewater as compared to aerobic treatment in system A in Figure 7. Micro-sieving and UASB could reduce oxygen demand for all kinds of industrial wastewater. In secondary treatment, the UASB reactor removes 15.8%-53.5%, 14.0%-49.0%, and 22.9%-51.1% of COD for three kinds of industrial wastewater. Because of the higher BOD/COD ratio of treated meat processing wastewater by micro-sieving, UASB could convert more COD to CH₄ than other industrial wastewater, which resulted in less oxygen demand to remove the remaining COD.

Figure 7 COD removal of primary and secondary treatment (1: Primary clarifier, 2: Micro sieving, 3: Aerobic treatment in system A, 4: Aerobic treatment in system B, 5: UASB reactor.)

Mainstream UASB converts biodegradable COD in wastewater to CH₄ for energy recovery. Since the BOD/COD ratio of treated wastewater by primary treatment is positively related to the influent wastewater quality as shown in Figure 6, CH₄ production/COD influent to secondary treatment (%) rises with increasing

biodegradability (BOD/COD ratio) in Figure 8. Since UASB removes COD through the conversion of organic matter to biogas, COD removal of UASB reactor also shows strong positive correlations with the BOD/COD ratio of raw wastewater, as shown in Figure 8. This suggests that the biodegradability of wastewater could be used for predicting methane conversion rate and COD removal of UASB reactor in the industrial wastewater treatment system with micro sieving. In addition, UASB shows excellent biogas production efficiency for treating industrial wastewater with high biodegradability.

Figure 8 CH₄ production/influent COD to UASB and COD removal of UASB reactor

3.2 Effluent wastewater quality

Since aerobic treatment in systems A and B is designed based on low effluent BOD and COD concentration, two treatment systems could achieve similar COD removal and concentration in the effluent, as shown in Figures 7 and 9. Table 4 shows current discharge standards of organics in industrial wastewater in different countries,

414 including European [103], the USA [11], China [104, 105], and India [106-108]. In
415 figure 9, effluent COD concentration are 116.61-1683.80, 356.13-2952.27 and 14.19-
416 680.48 mg/L, respectively. Most of the effluent wastewater quality in the two systems
417 does not meet the current discharge standards. This is due to a much high concentration
418 of COD, relatively low biodegradability (BOD/COD ratio), and the relatively high
419 content of refractory soluble organic matter. Most of the remaining COD, which is the
420 soluble non-biodegradable matter, is not easily removed by primary physical treatment
421 and biological processes. Physical-chemical treatment such as adsorption might be
422 required to remove soluble substances by the accumulation of those substances on
423 activated carbon to increase COD removal efficiency and meet the discharge
424 requirement. Figure 9 illustrates that the effluent of some meat processing wastewater
425 and textile wastewater achieve the discharge requirement of several countries due to
426 their low concentration of COD and relatively high BOD/COD ratio. Therefore, it is
427 necessary to study the relationship between the total COD removal of primary treatment
428 and biological processes and wastewater quality.

Figure 9 Effluent COD concentration of 3 industrial wastewater in two treatment systems

Table 4 Discharge standards of industrial wastewater in different countries

Type of wastewater Meat processing wastewater	Parameter	EU		USA		Canada		China		India	
		Mi n	Ma x	Mi n	Ma x	Mi n	Ma x	Mi n	Ma x	Mi n	Ma x
Meat processing wastewater	BOD (mg/L)	25		16	26	5	30	20	100	30	100
	COD (mg/L)	125						100	300	250	
Tannery wastewater	BOD (mg/L)									30	
	COD (mg/L)									250	
Textile wastewater	BOD (mg/L)							25		80	250
	COD (mg/L)							100		156	400

Table 5 shows the Pearson's correlations between COD removal, BOD/COD ratio, and TSS/COD ratio. The ratio between BOD/COD and the ratio between TSS and COD showed strong positive correlations with COD removal at the 0.01 level. Since the BOD/COD ratio and TSS/COD ratio affect COD removal of UASB and primary

treatment, regression models of COD removal are developed based on BOD/COD ratio and TSS/COD ratio. The equation for predicting COD removal of primary treatment and biological processes from BOD/COD and TSS/COD can be depicted as the following equation:

$$\text{COD removal (\%)} = 75.69(\text{BOD/COD ratio}) + 57.53(\text{TSS/COD ratio}) + 23.15 \quad R^2 = 0.929$$

(9)

The squared correlation coefficient R^2 represents that the BOD/COD ratio and TSS/COD ratio of influent wastewater can explain 92.9% of COD removal. The BOD/COD ratio and TSS/COD ratio are positively related to COD removal efficiency. Micro-sieving and UASB could achieve higher COD removal when treating industrial wastewater with higher particulate matter fraction and biodegradability. Effluent COD concentration could be calculated based on COD removal and influent COD concentration. Therefore, characteristics of wastewater could be used for predicting effluent COD concentration of industrial wastewater in a system with primary treatment and biological processes to determine if physical-chemical treatment is required.

Table 5 Correlations between COD removal, BOD/COD ratio and TSS/COD ratio of influent wastewater

Pearson Correlation	COD removal (%)
BOD/COD (%)	.712**
TSS/COD (%)	.804**

** At the 0.01 level (2-tailed), correlation is significant

3.3 Energy demand and production

3.3.1 Theoretical and actual energy production of UASB

In this study, empiric equations (1-5) were used to estimate theoretical COD removal and unit energy consumption of UASB, as shown in Table 6. Theoretical COD removal, unit methane production, and unit energy production at 25 °C are 54%-88%, 0.15-0.30 m³ CH₄/kg COD removal, and 0.52-1.03 kWh/kg COD.

Table 6 Theoretical COD removal, unit methane production, and unit energy production of UASB without primary treatment

BOD/COD ratio	0.57	0.46	0.29	0.53	0.34	0.30
COD concentration (mg/L)	2100.00	2350.00	4221.00	1697.00	3900.00	5422.25
COD removal (%)	88.08	85.45	53.85	82.66	54.56	79.01
Unit CH ₄ production (m ³ CH ₄ /kg COD removal at 0°C and 1 atm) *	0.27	0.22	0.17	0.26	0.21	0.14
Unit CH ₄ production (m ³ CH ₄ /kg COD removal at 25°C and 1 atm)	0.30	0.24	0.19	0.28	0.23	0.15
Unit energy consumption (kWh/kg COD removal)	1.03	0.83	0.65	0.97	0.80	0.52

* The following reaction is used for converting COD digested in UASB to methane:

1 kg COD digested could be converted to 0.25 kg CH₄ or 0.35m³ CH₄ theoretically at 0°C and 1 atm [95]

Table 7 lists the data of COD removal and methane production of UASB in treating food processing wastewater. These data were collected from published peer-reviewed papers [109-111]. Actual COD removal, unit methane production, and unit energy production at 25 °C are 43%-95%, 0.01-0.38 m³ CH₄/kg COD removal, and 0.03-1.30 kWh/kg COD. As shown in Table 6, 7, and Figure 10, theoretical energy productions are close to the actual values, which indicates the validity of empiric equations used in this study.

Table 7 Actual COD removal and unit methane production and unit energy production of UASB

HRT (h)	22	22	22	18	18	14	14	7.1	6.8	6.7	4.1	2.3
SRT (d)								60.3	23.4	14	14.4	3.3
Temperature (°C)	35	35	35	35	35	35	35	33	33	33	33	33
COD (mg/L)	2800	3200	4200	3000	6500	3900	6330	8201	5719	5256	5495	5514
COD removal (%)	83.2	84.4	89.2	82.5	90.6	78.5	85.7	78	73	77	83	68

L biogas/g COD removed	0.55 5	0.47	0.40 2	0.46	0.19 2	0.3	0.15 7					
L CH ₄ /kg SCOD removed (at 25°C and 1 atm)								21 3	25 4	28 3	20 1	19 9
Unit CH ₄ production (m ³ CH ₄ /kg COD removal at 0°C and 1 atm) *	0.34	0.29	0.25	0.29	0.12	0.19	0.11	0.07	0.15	0.23	0.15	0.11
Unit CH ₄ production (m ³ CH ₄ /kg COD removal at 25°C and 1 atm)	0.38	0.32	0.27	0.31	0.13	0.2	0.11	0.08	0.17	0.25	0.16	0.12
Unit energy consumption (kWh/kg COD removal)	1.30	1.10	0.94	1.08	0.45	0.70	0.37	0.27	0.58	0.85	0.56	0.41
Reference	[109]							[110]				
HRT (h)	24	24	24	24	24	24	24	24	24	24	24	24
SRT (d)												
Temperature (°C)	36	36	36	36	36	36	36	36	36	36	36	36
COD (mg/L)	3500	6000	10000	20000	28000	32000	35000	6000	10000	20000	28000	32000
COD removal (%)	>90	>90	>90	48	45	43	>90	>90	>90	95	72	68
Specific methane production (LCH ₄ /g COD added at 36 °C)	0.21	0.15	0.12	0.02	0.01	0.04	0.28	0.19	0.18	0.21	0.08	0.04
Unit CH ₄ production (m ³ CH ₄ /kg COD removal at 0°C and 1 atm) *	0.21	0.15	0.12	0.04	0.02	0.1	0.27	0.19	0.18	0.2	0.1	0.05
Unit CH ₄ production (m ³ CH ₄ /kg COD removal at 25°C and 1 atm)	0.23	0.16	0.13	0.04	0.02	0.1	0.3	0.2	0.19	0.21	0.1	0.06
Unit energy consumption (kWh/kg COD removal)	0.78	0.56	0.44	0.14	0.07	0.03	1.04	0.70	0.67	0.74	0.37	0.20
Reference	[111]											

475 * Unit CH₄ production at the standard temperature and pressure (STP) is estimated
476 based on the assuming methane/biogas ratio of 70% [112], 0°C, and 1 atm.

Figure 10 Actual and Theoretical unit energy production of UASB

3.3.2 Theoretical and actual energy consumption of PN/A

Table 8 lists the actual unit energy consumption of PN/A is 0.8-1.92 kWh/kg N removed. Based on equations (9-10), 1.32kWh/kg $\text{NH}_4^+ \text{--N}$ was used as the theoretical unit energy consumption of PN/A, which is close to the actual value, as shown in Figure 11. This proves the validity of the theoretical unit energy consumption. According to the benchmarking method reported by Yang et al. [113], the mean actual unit energy consumptions of 1.4 kWh/kg $\text{NH}_4^+ \text{--N}$ could be selected as the benchmark data for comparing with actual unit energy consumption to check the energy efficiency of PN/A reactor.

Table 8 Energy consumption of PN/A reactors.

Plant	Reactor type	Unit energy demand (kWh/kg $\text{NH}_4^+ \text{--N}$ removed)	Reference
Apeldoorn	SBR	1.1	[114]
Balingen	SBR	0.92	
Heidelberg	SBR	1.67	
Ingolstadt	SBR	1.92	
Nieuwegein	SBR	0.8	
Zurich	SBR	1.11	
Olburgen		1.86	[115]
Malmö	MBBR	1.45-1.75

Figure 11 Actual and Theoretical unit energy consumption of PN/A

3.3.3 Energy consumption and production of WWTP

Electricity consumption of a WWTP is mainly from the wastewater pump station, aeration equipment, and sludge treatment. Secondary biological treatment consumes 50–70% of the overall energy consumption of a WWTP [98]. Therefore, the energy required by aeration was the dominant energy consumption. Figure 12 shows that electricity consumption rises as the influent concentration of $\text{NH}_4^+\text{-N}$ and soluble biodegradable organic nitrogen (sbON) increases. Therefore, unit energy consumption (kWh/kg N removed) is used for comparing energy efficiency of different industrial wastewater systems as shown in Figure 13. The oxygen requirement of PN/A process and nitrification process are 1.83 and 4.57 $\text{g O}_2/\text{g NH}_4\text{-N}$ converted. PN/A process in system B effectively reduces aeration consumption for removing $\text{NH}_4\text{-N}$. Therefore, system B shows lower unit energy consumption than system A. In Figure 13, mean unit energy consumptions of system B for meat processing wastewater, tannery

505 wastewater, and textile wastewater are 1.49, 1.37, and 1.39 kWh/kg N removal,
 506 respectively. Since primary treatment and UASB removes COD without using oxygen,
 507 most of O₂ is used for the PN/A process, especially in system B. Therefore, mean unit
 508 energy consumptions of system B are close to than actual unit energy consumption of
 509 PN/A, as shown in Figure 11.

510

511 **Figure 12** Electricity consumption and influent NH₄⁺-N and sbON

Figure 13 Unit electricity consumption

Except for BOD that is converted to CO₂ in aerobic treatment, most of soluble BOD (sBOD) in industrial wastewater and biodegradable particulate BOD (bpBOD) in primary and secondary sludge are converted to CH₄ to produce electricity and heat by UASB and side stream anaerobic digester. Figure 14 illustrates energy production rises with increasing influent BOD concentration. The unit energy production (kWh/kg BOD removal) is used as an indicator in assessing the influence of different industrial wastewater on two treatment systems, as shown in Figure 15. The average unit energy production of system B for meat processing wastewater, tannery wastewater, and textile wastewater are 1.80, 1.77, and 1.73 kWh/kg BOD removal, respectively. The unit energy production for food processing wastewater is higher than that of other industrial wastewaters. Meat processing wastewater has higher BOD concentration and biodegradability (BOD/COD ratio), as shown in Table 1 and Figure 3. This increases biogas production efficiency and unit energy production of UASB reactors, as shown

527 in Figure 16. In addition, sludge production from the PN/A process and denitrification
 528 process increase CH_4 production of side stream anaerobic digester. Therefore, the
 529 energy positive system for treating meat processing wastewater could produce more
 530 energy with the same BOD removal than that for treating tannery wastewater and textile
 531 wastewater.

532
 533 **Figure 14** Electricity production and influent BOD
 534

Figure 15 Unit electricity production

Figure 16 Unit energy production of UASB

3.3.4 Energy recovery

Figure 17 shows the influence of different industrial wastewater on energy recovery of two treatment systems. System A for treating industrial wastewater could not produce enough electricity to satisfy the energy demand for oxygen production due to the energy ratio of less than 1. Since UASB effectively converts COD to CH_4 and PN/A decreases energy consumption for removing N, innovative technologies could help industrial wastewater treatment achieve electrical self-sufficiency, as shown in Figure 17. Meat processing wastewater has higher BOD concentration and BOD/COD ratio. However, N concentration of meat processing wastewater is higher than other industrial wastewaters. Energy consumption and energy production are influenced by BOD and N concentration, respectively. In system B, energy recovery ratio is positive related to BOD/N ratio, as shown in Figure 18. High BOD and N concentration of meat processing wastewater leads to relatively lower BOD/COD ratio and energy recovery ratio. Although textile wastewater has lower BOD concentration, the value of the energy ratio for textile treatment system B could be as high as 17.7 because of lower N concentration and higher BOD/N ratio. The minimal energy ratio is 7.0 which is seven times higher than 1. The mean energy ratio is 14.3. Therefore, BOD/N ratio significantly affects energy recovery of treatment system with innovative technologies.

Figure 17 Energy recovery ratio of system A and B

Figure 18 Energy recovery ratio as a function of daily influent BOD/ TN ratio in system B

3.4 Environmental indicators

The contributors of system A and B to global warming and eutrophication potential are shown in Figure 19 and 20. Since the global warming potential is higher than 0, activated sludge process with nitrification-denitrification for treating industrial wastewater could not be considered as the sustainable design. Energy significantly affects global warming potential of treatment systems. System B could produce enough electricity to satisfy the aeration demand. The energy production could offset the overall global warming potential in system B, as shown in Figure 19. Therefore, achieving energy positive by innovative technologies could effectively reduce impacts of industrial wastewater treatment on the global warming. Due to high energy recovery ratio, the eutrophication potential of treatment system B is lower than that of system A, as shown in Figure 20. Since the eutrophication potential is affected by effluent pollutant mass, meat processing wastewater treatment has higher eutrophication potential than textile wastewater treatment. Many researchers did not consider the physical-chemical treatment when designing wastewater treatment system [76, 77, 116]. The physical-chemical treatment is not necessary because non-biodegradable COD of municipal wastewater is low enough to meet discharge requirements. However, meat processing wastewater has high concentration of COD and non-biodegradable COD. This results in a high eutrophication potential of food processing wastewater treatment. UASB and activated sludge process could not remove non-biodegradable matter. Therefore, the physical-chemical treatment is required to be applied in the future food processing wastewater treatment design for removing non-biodegradable COD.

Figure 19 Global warming potential of 3 industrial wastewater in two treatment systems

Figure 20 Eutrophication potential of three industrial wastewaters

in two treatment systems

3.5 Cost analysis

Unit cost analysis of treatment systems based on different industrial wastewater quality compares the cost of these systems. Since COD removal by primary treatment and secondary treatment are positively related to TSS/COD ratio and BOD/COD ratio, unit cost metric (\$/kg COD_{removed}) is used as the indicator in this study. Figure 21 compares the unit cost (\$/kg COD_{removed}) of two systems for treating different industrial wastewater. Although application of UASB and PN/A in system B increase the corresponding cost, UASB and PN/A reduces influent BOD and N loading and required size of activated sludge process with nitrification-denitrification. Figure 21 demonstrates that the unit cost of system B is lower than that of system A. Since economic income due to energy recovery and cost saving is higher than the increased cost of innovative technologies, innovative biological technologies could replace the old process. In system B, the average unit cost for meat processing wastewater, tannery wastewater, and textile wastewater are 0.54, 0.57, and 1.12 \$/kg COD removal, respectively. The unit cost for meat processing wastewater is lower than that for the other wastewaters. Compared with other wastewater, meat processing wastewater has a higher biodegradability and concentration of BOD, which could produce a large amount of CH₄ for energy recovery to reduce the unit cost of a treatment system. On the other hand, COD removal strongly affects unit costs of the main unit process as shown in Figures 22. The unit cost of UASB systems decrease with increasing COD removal. The unit capital cost (\$/reactor volume m³) of UASB is much higher than that of activated sludge tank for small-sized WWTPs, as shown in Table 9. The total cost of treatment system is significantly by the cost of UASB. Although textile wastewater has the highest energy recovery ratio, the COD concentration of textile wastewater is

lower than that of other wastewaters. This leads to higher unit costs of the UASB. The meat processing wastewater system consumes more oxygen for removing N in PN/A. However, this process increases the CH₄ production of AD through increasing biomass. Higher biodegradability and pollutant concentration reduce the unit cost of the meat processing wastewater treatment system. Therefore, it is more economical to treat meat processing wastewater with innovative technologies.

Figure 21 Unit cost of different industrial wastewater treatment

Figure 22 Unit cost of UASB

Table 9 Unit capital cost for different treatment capacity of WWTPs (Population Equivalents (PE.))

Unit capital cost (US\$ / reactor volume m ³)	UASB		Activated sludge tank		Reference
Capacity (PE.)	Min	Max	Min	Max	
25,000	600	1000	220	300	[76]
50,000	500	700	180	250	
100,000	350	500	150	200	
200,000	250	400	120	170	

4. Conclusions

In the current study, an Excel-based model was developed to compare the unit energy and cost of energy positive systems for treating different kinds of industrial wastewater. Results showed that micro-sieving could remove 35.36%, 39.08%, and 32.50% of COD for tannery, meat processing, and textile wastewater, respectively. Due to the relatively high TSS/COD ratio, primary treatment could achieve high COD removal efficiency of textile wastewater with low TSS concentration as compared to

tannery wastewater. UASB reactor could remove 15.8%-53.5%, 14.0%-49.0%, and 22.9%-51.0% of COD for three kinds of wastewater, respectively. UASB converts more COD to CH₄ in meat process wastewater with high BOD concentration because of the high BOD/COD ratio. Pearson correlation analysis shows that the TSS/COD ratio and BOD/COD ratio are the key parameters in determining COD removal and methane conversion rate of primary treatment and secondary treatment. These regression equations could be used to predict COD removal by the primary and biological processes as follows:

$$\text{COD removal (\%)} = 75.69(\text{BOD/COD ratio}) + 57.53(\text{TSS/COD ratio}) + 23.15 \quad R^2 = 0.929$$

For meat processing wastewater, tannery wastewater, and textile wastewater, the mean unit energy consumptions were 1.49, 1.37, and 1.39 kWh/kg N removal, which are close to actual unit energy consumption of PN/A process. Mean unit energy production for three types of wastewater in innovative system are 1.80, 1.77, and 1.73 kWh/kg BOD removal, respectively. The energy positive system for treating meat processing wastewater could produce more energy for removing the same amount of BOD than other than other industrial wastewater treatment systems. The average unit cost for meat processing wastewater, tannery wastewater, and textile wastewater are 0.54, 0.57, and 1.12 \$/kg COD removal, respectively. Textile wastewater treatment has the highest energy recovery ratio. However, the low COD concentration of textile wastewater leads to high unit cost of system. Meat processing wastewater has higher COD concentration and biodegradability than other wastewaters, which reduce unit cost of UASB and increases electricity production through increasing COD loading rate to UASB and AD. A low unit cost of UASB and a high CH₄ production rate improves the unit cost of meat processing wastewater treatment systems. Therefore, it is more

economical and easier to treat meat processing wastewater with micro sieving, UASB, and PN/A technologies than other industrial wastewaters. Due to high energy recovery, innovative technologies could effectively reduce effect of industrial wastewater treatment on the global warming. However, meat processing wastewater treatment with innovative technologies shows high eutrophication potential because of its high non-biodegradable COD concentration. UASB with anammox treatment for treating meat processing wastewater could not be considered as the sustainable option when the eutrophication criterion and discharge requirement are prioritized. Therefore, physical-chemical treatment may be required in the future food processing wastewater treatment design to remove non-biodegradable COD. The economic advantages and limitations of innovative technologies in treating industrial wastewater have been quantified by using unit energy and cost per kg pollutant removed which provide valuable references for future sustainable design of industrial wastewater treatment systems.

5. Additional information

Availability of data and materials

The data supporting the conclusions of this study are available within the article.

Competing interests

The authors claim no conflict of interests.

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Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Jinze Li. The first draft of the

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Figures

Figure 1

Schematic graphs of wastewater treatment system A- activated sludge process with nitrification-denitrification

Figure 2

Scheme of wastewater treatment system B: UASB and anammox treatment

Figure 3

TSS/COD ratio and BOD/COD ratio for different industrial wastewater

Figure 4

COD removal of primary treatment for different industrial wastewater

Figure 5

Variation of COD removal in primary treatment with TSS/COD ratio

Figure 6

Variation of biodegradability after primary treatment

Figure 7

COD removal of primary and secondary treatment (1: Primary clarifier, 2: Micro sieving, 3: Aerobic treatment in system A, 4: Aerobic treatment in system B, 5: UASB reactor.)

Figure 8

CH₄ production/influent COD to UASB and COD removal of UASB reactor

Figure 9

Effluent COD concentration of 3 industrial wastewater in two treatment systems

Figure 10

Actual and Theoretical unit energy production of UASB

Figure 11

Actual and Theoretical unit energy consumption of PN/A

Figure 12

Electricity consumption and influent $\text{NH}_4^+\text{-N}$ and sbON

Figure 13

Unit electricity consumption

Figure 14

Electricity production and influent BOD

Figure 15

Unit electricity production

Figure 16

Unit energy production of UASB

Figure 17

Energy recovery ratio of system A and B

Figure 18

Energy recovery ratio as a function of daily influent BOD/ TN ratio in system B

Figure 19

Global warming potential of 3 industrial wastewater in two treatment systems

Figure 20

Eutrophication potential of three industrial wastewaters in two treatment systems

Figure 21

Unit cost of different industrial wastewater treatment

Figure 22

Unit cost of UASB